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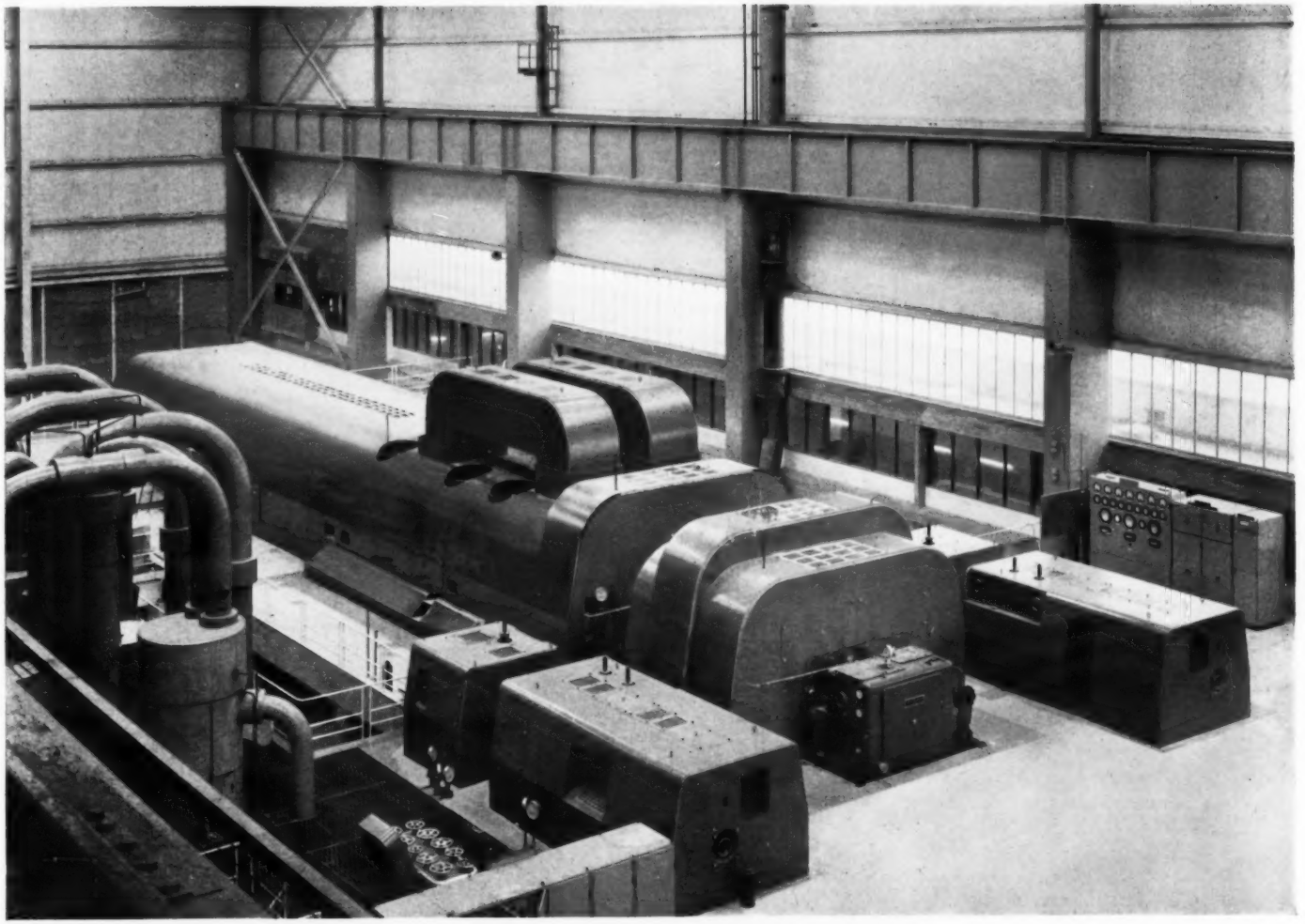


The turbine room in High Marnham power station of the Central Electricity Generating Board, East Midlands Division, showing one of the five 200 MW 'English Electric' turbo-alternator sets

High Marnham Power Station of the Central Electricity Generating Board, East Midlands Division

THE DECISION OF THE British Electricity Authority, during the year 1954, to build a new generating station in the East Midlands Division comprising five 200 MW reheat turbo-alternator sets, represented a bold and imaginative step forward in the generation of electrical power in Great Britain.

High Marnham, situated in a typical Midland agricultural area, afforded the right combination of facilities—rail, water and coal. To-day, tall tapering chimneys and massive concrete cooling towers dominate the landscape for miles around. At their foot the main building structure with its aluminium-clad walls stretches into the distance, the complete station in its several aspects embodying the combined skill of designers, civil engineers and plant builders.

The site is on the west bank of the river Trent, and is approached via the main railway line connecting Chesterfield with Lincoln. Preparatory building work commenced in February 1956 and the first generating set was synchronised in October 1959.

The five 200 MW turbo-alternator units are arranged longitudinally in the station at 120 ft centres, having the main auxiliaries parallel to the machines. Conforming with modern trends, the plant is arranged on the unit system, i.e. one boiler for each turbine.

High Marnham station is of special interest, being one of the first in Great Britain in which the advantages of using high-pressure high-temperature steam with reheat have been exploited practically. The turbines operate with steam at 2350 p.s.i.g., 1050°F, at the turbine stop valve, the steam being reheated to 1000°F, at 426 p.s.i.g., before the intermediate-pressure cylinder. At M.C.R., the final feed temperature after six-stage feed heating is 460°F, with a corresponding vacuum at the turbine exhaust flange of 28.7 in. Hg.

The English Electric Company's contribution comprises the five turbo-alternator sets, feed heating and condensing plants, main transformers, 415 V switchgear, and the motor drives for the boiler fans and a number of pumps.

STEAM TURBINES

The longitudinal section of the turbine is shown in Fig. 1, from which it will be apparent that its design incorporates several new features. The machine comprises a three-cylinder 3000 r.p.m. reheat turbine having a reversed-flow type of high-pressure cylinder and incorporating a double-casing construction at its high-pressure end. A partial double-casing design is also employed for the first few stages of the intermediate-pressure cylinder. There are three flows of low-pressure blading exhausting into a common exhaust chamber and single-shell condenser. The turbine drives, in tandem, a 3000 r.p.m. 200 MW hydrogen-cooled alternator.

Steam is supplied to the turbine through two main steam pipes which connect direct from the boiler to two cast alloy-steel chests disposed symmetrically about the H.P. end of the turbine. Each of the main steam chests contains a combined stop and emergency valve, which can be operated locally or from the control room and can be tripped by the action of various automatic electrical and hand-operated protective devices. From the chests, the steam flows to the high-pressure cylinder through two single-seated sequentially opening throttle valves arranged in parallel in each chest,

The turbine room in High Marnham [illegible] the five 200 MW 'English Electric' turbo-alternator sets

thence through four 5½ in. bore loop pipes interconnected in pairs just before entering the casing radially at top and bottom. The use of separate chests and U-loops between the chests and casing ensures flexibility of piping and minimises the thrust loads on the turbine.

To prevent the increase in overspeed which would be caused in the event of a load rejection by stored steam in the reheater pipeline, if this were allowed to pass through the I.P. and L.P. cylinders, governor-controlled interceptor valves are fitted in chests ahead of the I.P. cylinder.

These interceptor valves are not required to control the flow of steam to the set when the load is being increased or decreased at a steady controlled rate. They are normally fully open above 25% M.C.R. and only begin to close after 3% rise in speed above normal has occurred. Once closure begins it proceeds rapidly, and the overall time of closure of the reheat valves is less than that of the main governing valves. Just as emergency stop valves are fitted at the H.P. inlet to the turbine to act as a second line of defence should the governing valves stick or for any other reason be slow in closing, it was considered advisable to reinforce the protection afforded by the interceptor valves by including reheat emergency stop valves just ahead of the interceptor valves. These stop valves are under the control of the overspeed governor and other emergency devices available to the turbine and control room operators.

Casings

The detailed design and construction of the casings (Fig. 2) is of interest, emphasising as it does the manner in which the problems arising from the employment of a reheat cycle have been overcome. These problems concern: (1) the point at which steam is taken from the turbine for reheating; (2) the design of bolting to withstand the high-pressure loads on cylinder joint flanges, associated with the relatively low bolt stresses determined by a low creep rate at high temperature.

The H.P. steam inlet is located approximately half-way along the outer cylinder. The exhaust steam from the inner casing returns along the outer side of the latter, cooling the inlet pipe on the way. The inner casing is located axially by guides in the plane of the steam admission connections.

The two inlet pipes slide in piston-ring telescopic joints in the inner casing, thus accommodating radial expansion between outer and inner casings. The piping is also hotter than the outer casing, and differential radial expansion is allowed for by the flexible collar shown.

The intermediate-pressure cylinder shown in Fig. 1 is also arranged as a double casing

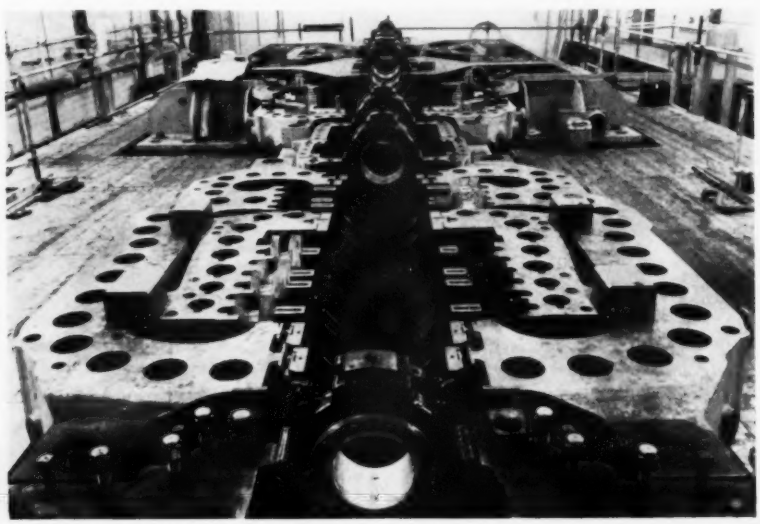
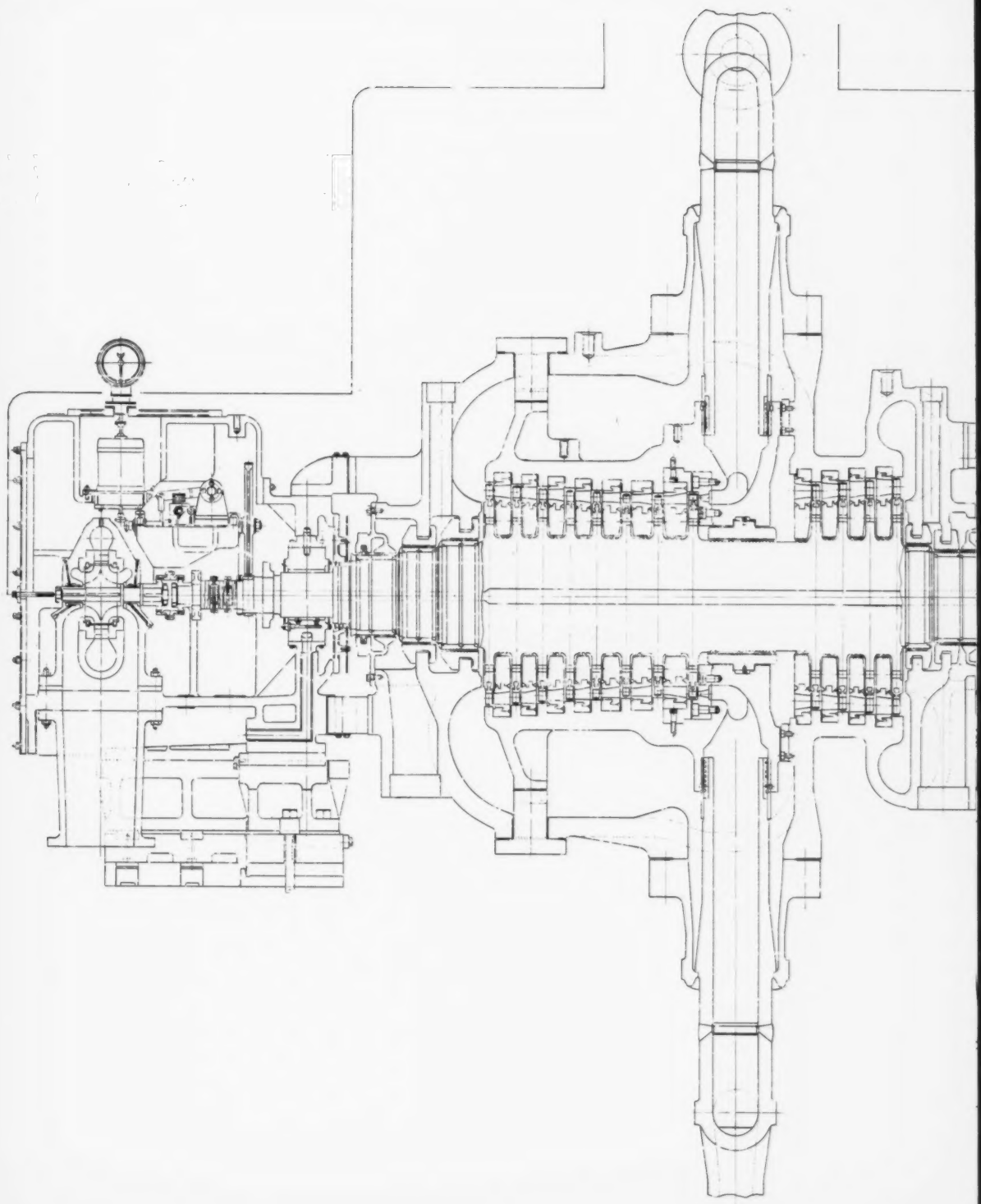


Fig. 2.—Bottom casings, showing high-pressure double-casing design with diaphragms in position



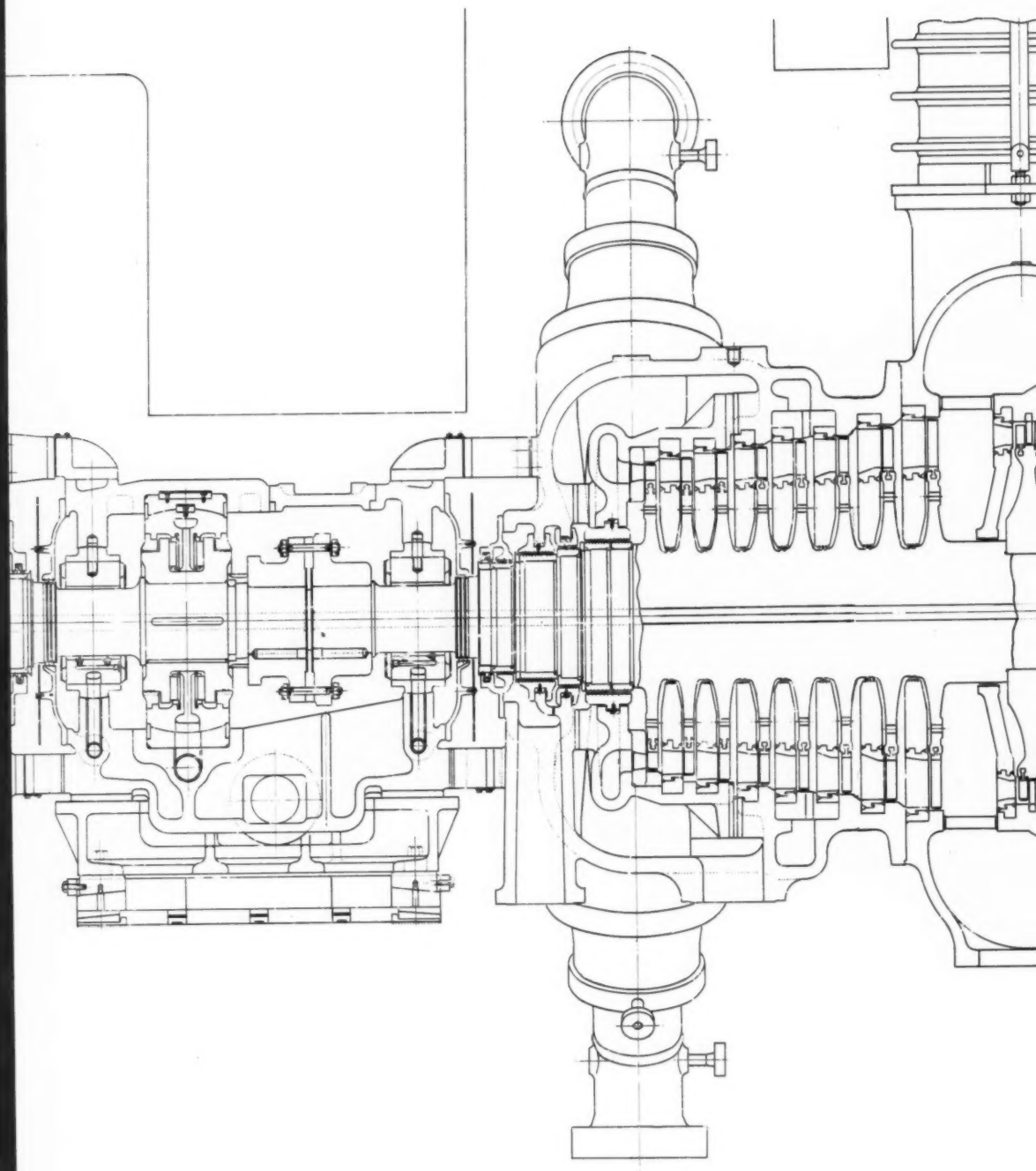
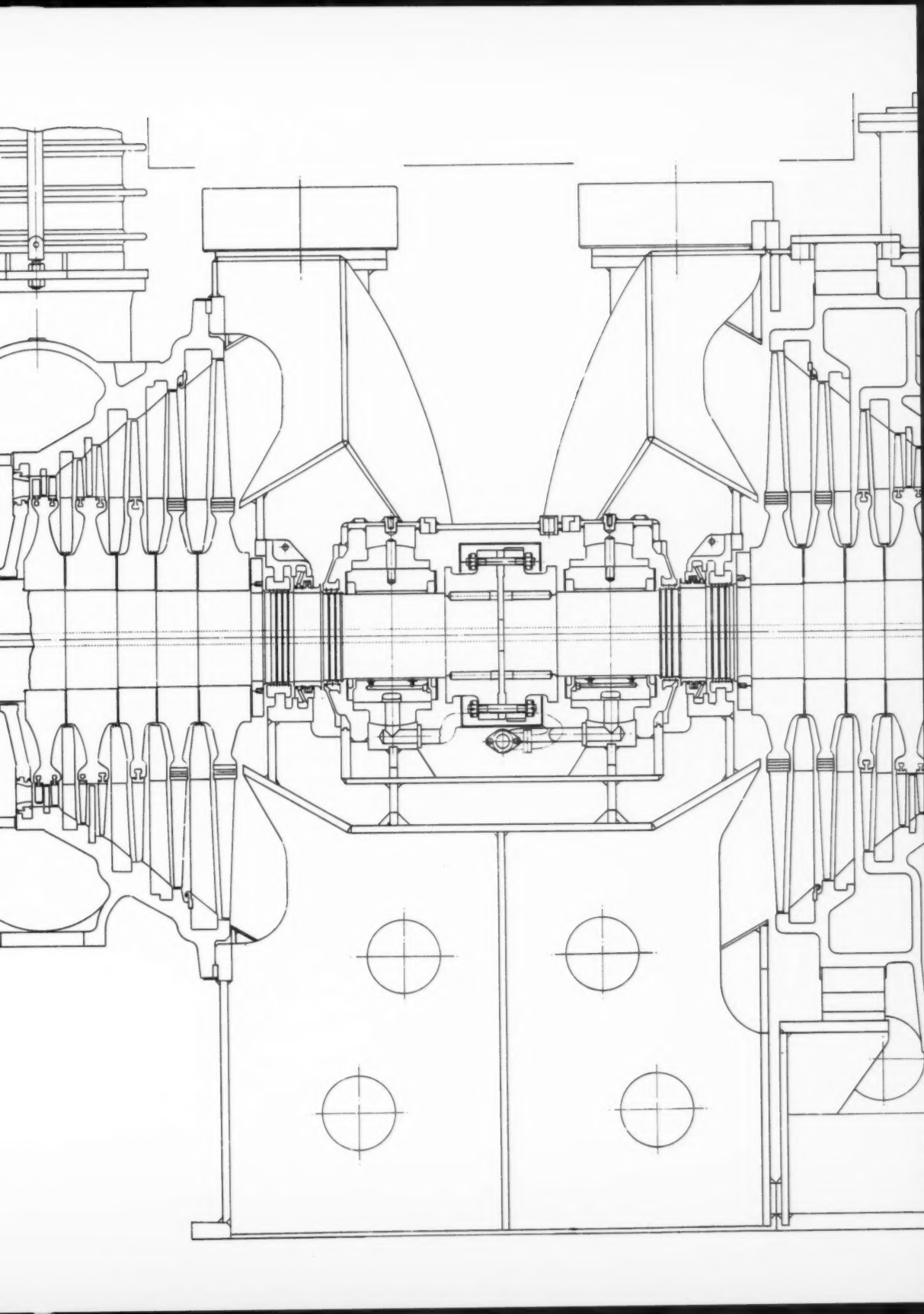
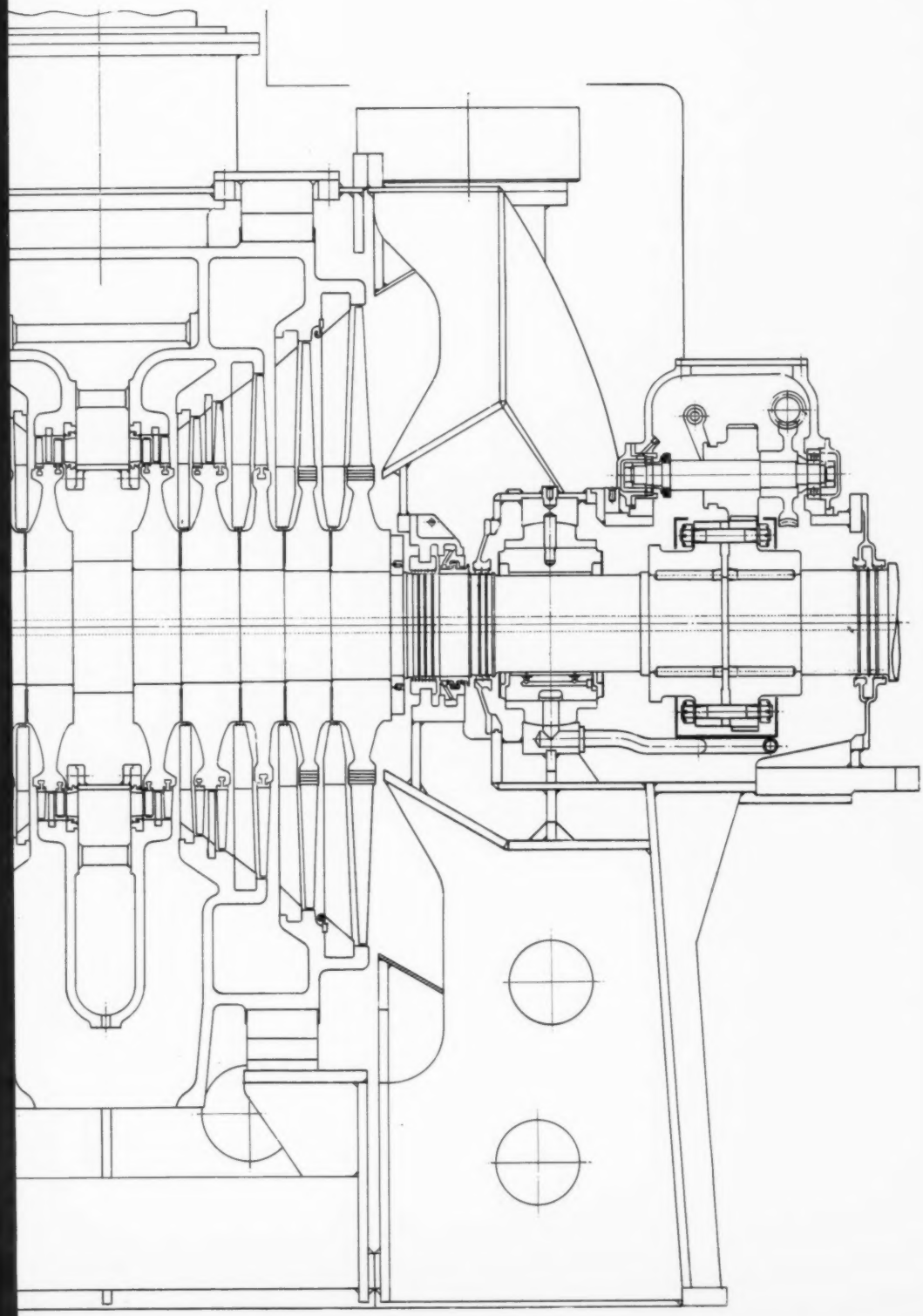


Fig. 1.—*Sectional arrangement of the turbine*





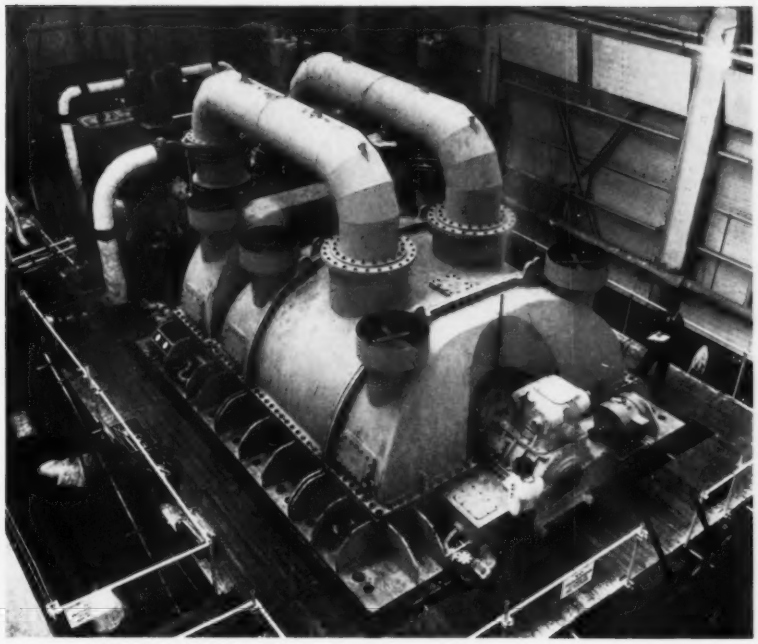


Fig. 3.—Turbine on test at The English Electric Company's Rugby Works

construction at the high-pressure end. Steam is fed into the nozzle chamber by means of four radial pipes. These flanged pipes are inserted after the inner casing has been centred within the outer, and the top half of the outer casing has been secured in position.

The H.P. and I.P. outer casings are molybdenum-vanadium steel castings, the corresponding inner casings being cast in a chrome-molybdenum-vanadium-tungsten alloy.

As the steam temperature at the inlet to the L.P. cylinder is higher than is normal in a non-reheat set, the L.P. casings which carry the fixed blading and diaphragms are cast in steel instead of iron. Because of its massive proportions, the exhaust chamber has been manufactured in three sections which have been seal-welded after erection at site.

Rotors

The H.P. and I.P. rotors, being subjected to high inlet steam temperatures, are of solid construction with gashed discs. The exhaust end of the I.P. rotor carries separately mounted discs for the single-flow L.P. section. Similarly, the remaining two flows of the double-flow L.P. rotor are of built-up construction in which large discs are mounted on a shaft forging.

For the H.P. and I.P. shafts, molybdenum-vanadium steels having good creep-resisting properties are employed. The L.P. shafts are forged from high-quality carbon steel.

Conforming with the modern trend in design for the larger ratings, the shafts are solidly coupled. The thrust block is located in the pedestal between the H.P. and I.P. rotors. The rotors are free to expand axially on either side of the thrust bearing; axial clearances provided between the nozzles or fixed blading and the rotor blading allow for the differential expansion between rotors and casings which inevitably occurs during starting-up or shutting-down the machine, or as a result of change of load. It is therefore not necessary to move the rotors axially at any time when operating the machine, and no provision is made for doing this.

The diaphragms in the H.P. and I.P. cylinders are of molybdenum-vanadium steel. The impulse stages of the L.P. cylinder diaphragms are of $\frac{1}{2}$%

molybdenum steel. The L.P. turbine is provided with reaction blading except for the inlet stage, where an impulse stage is fitted.

Blading

The moving blading for the H.P. and I.P. cylinders is of high-tensile stainless iron. For the L.P. cylinders stainless iron blading is used with the exception of the last four rows in the L.P. rotor which, due to the higher operating stresses, are of manganese-nickel steel, chromium plated.

All the moving blading is machined out of solid bar material and has integral roots. The blade fixings are of various types suited to the stresses imposed in service, but mention may be made of the fixings of the long blades in the last two rows of the L.P. turbine. These are of the ' side-entry ' type in which each root is held in a separate groove in the disc head, the grooves being cut across the head in an approximately axial direction. The advantage of this is that bending stresses are virtually eliminated both in the blade root and in the disc head, so that the total resultant stress at this vital point is much reduced.

Shaft Gland Packing System

The turbine shaft glands are of the steam-packed labyrinth type throughout.

A semi-automatic system of control has been adopted in which a single valve requires operating only when starting and shutting down, no adjustments to the control being required during normal operating periods. This system, which has been developed and patented by The English Electric Company under the title ' Vacuum Seal ' system, has already been successfully applied to a number of machines, the chief merit being simplicity since the only automatic valve used is a conventional pressure-reducing valve.

The essential feature is that the outer leak-off pockets of the H.P. and I.P. cylinders are connected by ample piping to a low-pressure stage so that they are at a vacuum at all loads. Beyond these vacuum pockets the glands are sealed continuously with steam from the main steam supply. This very small extra flow of steam is not measurable in the total and ensures a steady state of steam conditions in the glands, thus avoiding the hazards associated with other gland systems in which cold steam and even water may enter the glands on reduction of load.

The slight surplus of sealing steam supplied to each gland is condensed by individual gland vent condensers, and any variation in the surplus due to fluctuation in flow of steam through the glands caused by load changes is absorbed by these condensers. The condensed gland steam is visible as it flows through enclosed tundishes, and provides a positive check on the sealing in each individual gland.

Governing

The governor and control gear is shown diagrammatically in Figs. 4 and 5, and consists essentially of three parts:—

1. Speed-sensitive governor for control of H.P. throttle valves and I.P. interceptor valves for synchronising duties, and to hold the speed down on moderate load rejections.
2. Fast-acting secondary governor sensitive to heavy load rejections, having an overriding control of the H.P. throttle valves and I.P. interceptor valves.

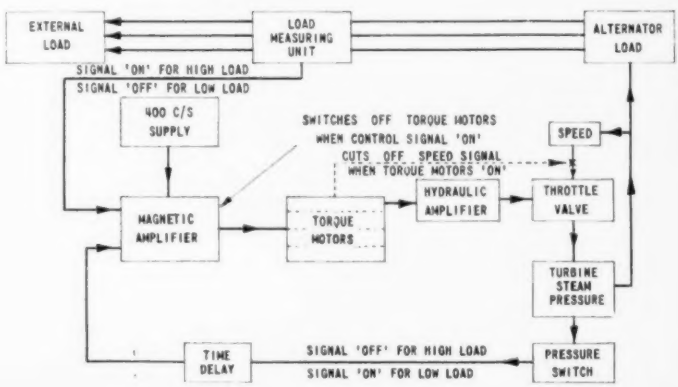
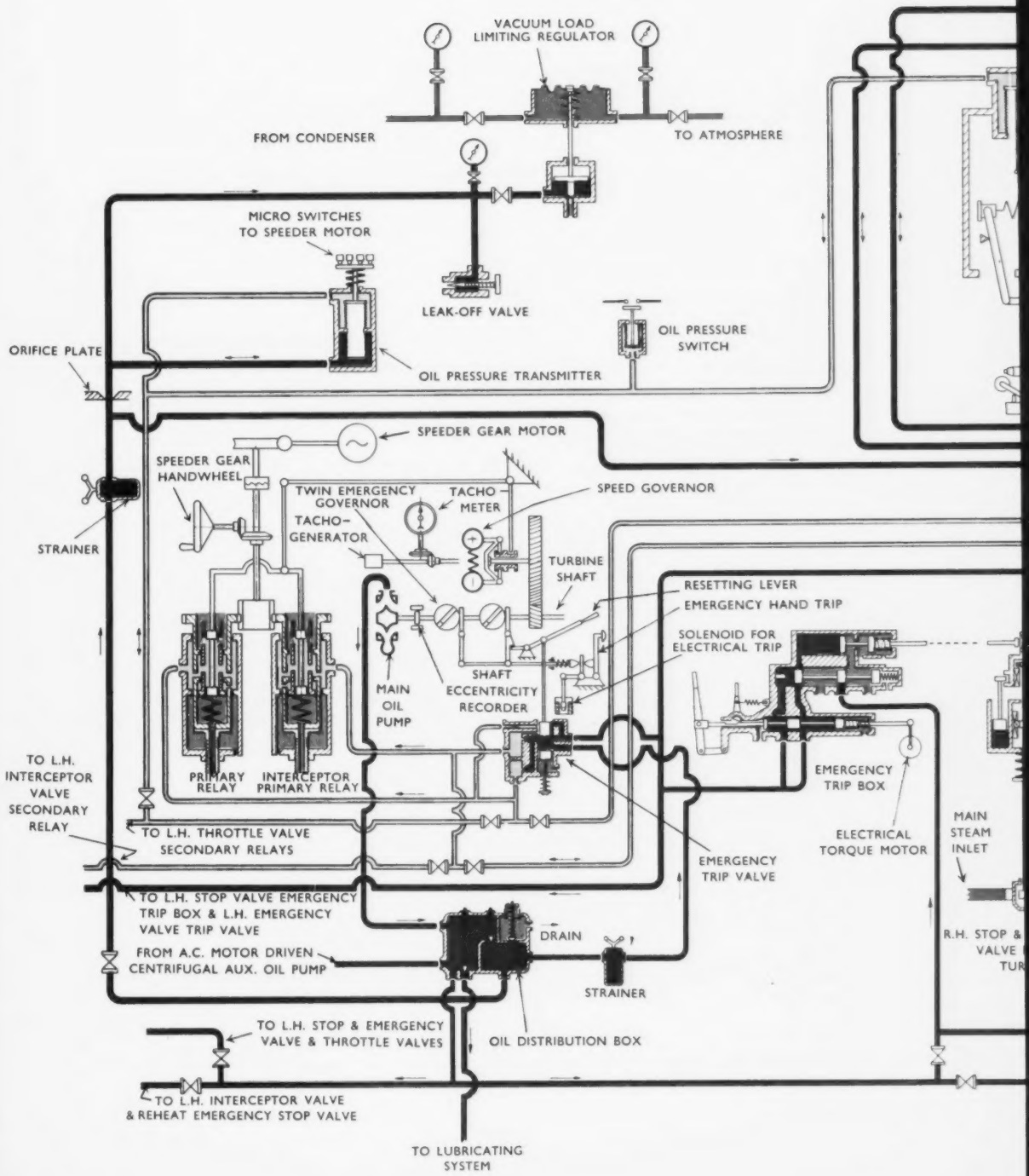


Fig. 4.—Block diagram of secondary governor


VACUUM LOAD LIMITING REGULATOR
FROM CONDENSER
TO ATMOSPHERE
MICRO SWITCHES TO SPEEDER MOTOR
LEAK-OFF VALVE
OIL PRESSURE SWITCH
ORIFICE PLATE
OIL PRESSURE TRANSMITTER
SPEEDER GEAR MOTOR
SPEEDER GEAR HANDWHEEL
TWIN EMERGENCY GOVERNOR
TACHO METER
SPEED GOVERNOR
TACHO-GENERATOR
STRAINER
TURBINE SHAFT
RESETTING LEVER
EMERGENCY HAND TRIP
SOLENOID FOR ELECTRICAL TRIP
MAIN OIL PUMP
SHAFT ECCENTRICITY RECORDER
PRIMARY RELAY
INTERCEPTOR PRIMARY RELAY
EMERGENCY TRIP BOX
ELECTRICAL TORQUE MOTOR
MAIN STEAM INLET
TO L.H. INTERCEPTOR VALVE SECONDARY RELAY
TO L.H. THROTTLE VALVE SECONDARY RELAYS
EMERGENCY TRIP VALVE
TO L.H. STOP VALVE EMERGENCY TRIP BOX & L.H. EMERGENCY VALVE TRIP VALVE
DRAIN
FROM A.C. MOTOR DRIVEN CENTRIFUGAL AUX. OIL PUMP
STRAINER
TO L.H. STOP & EMERGENCY VALVE & THROTTLE VALVES
OIL DISTRIBUTION BOX
TO L.H. INTERCEPTOR VALVE & REHEAT EMERGENCY STOP VALVE
TO LUBRICATING SYSTEM

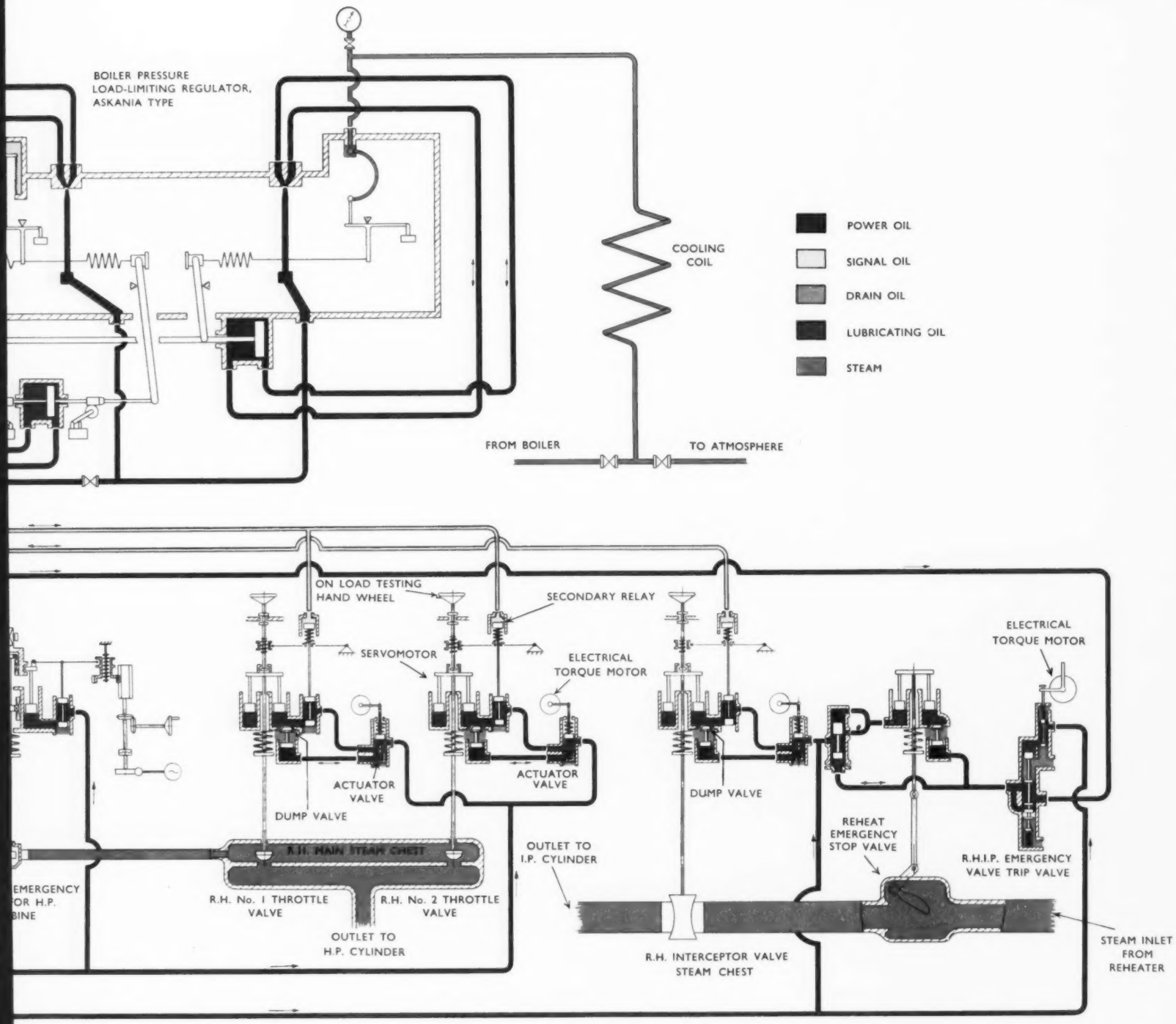
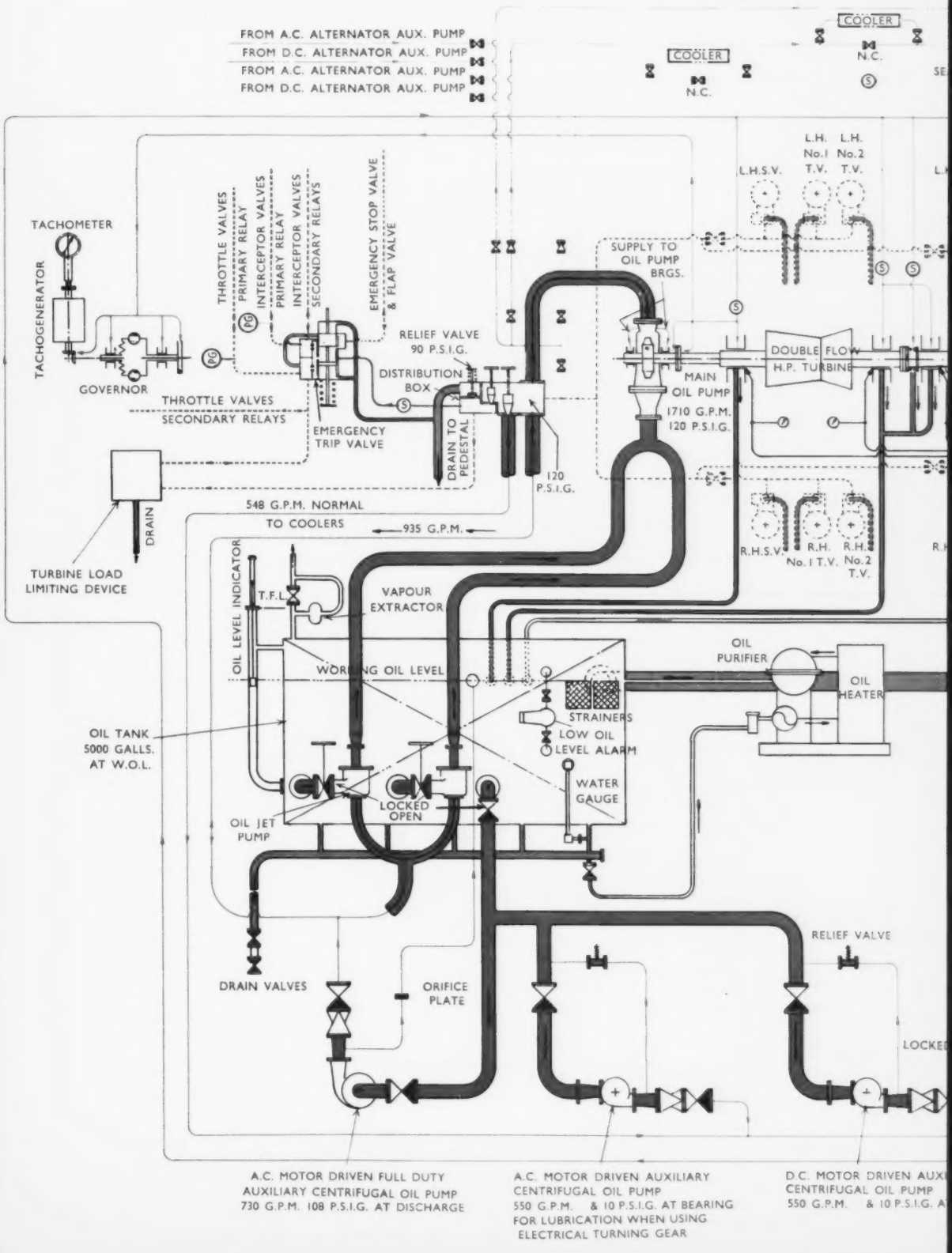


Fig. 5.—Diagrammatic arrangement of hydraulic governor gear


FROM A.C. ALTERNATOR AUX. PUMP
FROM D.C. ALTERNATOR AUX. PUMP
FROM A.C. ALTERNATOR AUX. PUMP
FROM D.C. ALTERNATOR AUX. PUMP
COOLER
N.C.
COOLER
N.C.
L.H.S.V.
L.H. No.1 T.V.
L.H. No.2 T.V.
TACHOMETER
TACHOGENERATOR
GOVERNOR
THROTTLE VALVES
PRIMARY RELAY
INTERCEPTOR VALVES
PRIMARY RELAY
INTERCEPTOR VALVES
SECONDARY RELAYS
EMERGENCY STOP VALVE & FLAP VALVE
SUPPLY TO OIL PUMP BRGS.
RELIEF VALVE 90 P.S.I.G.
DISTRIBUTION BOX
THROTTLE VALVES SECONDARY RELAYS
EMERGENCY TRIP VALVE
DRAIN TO PEDESTAL
120 P.S.I.G.
DOUBLE FLOW H.P. TURBINE
MAIN OIL PUMP 1710 G.P.M. 120 P.S.I.G.
548 G.P.M. NORMAL TO COOLERS
935 G.P.M.
DRAIN
TURBINE LOAD LIMITING DEVICE
R.H.S.V.
R.H. No.1 T.V.
R.H. No.2 T.V.
OIL LEVEL INDICATOR
T.F.L.
VAPOUR EXTRACTOR
WORKING OIL LEVEL
OIL PURIFIER
OIL HEATER
STRAINERS
LOW OIL LEVEL ALARM
OIL TANK 5000 GALLS. AT W.O.L.
WATER GAUGE
LOCKED OPEN
OIL JET PUMP
RELIEF VALVE
DRAIN VALVES
ORIFICE PLATE
A.C. MOTOR DRIVEN FULL DUTY AUXILIARY CENTRIFUGAL OIL PUMP 730 G.P.M. 108 P.S.I.G. AT DISCHARGE
A.C. MOTOR DRIVEN AUXILIARY CENTRIFUGAL OIL PUMP 550 G.P.M. & 10 P.S.I.G. AT BEARING FOR LUBRICATION WHEN USING ELECTRICAL TURNING GEAR

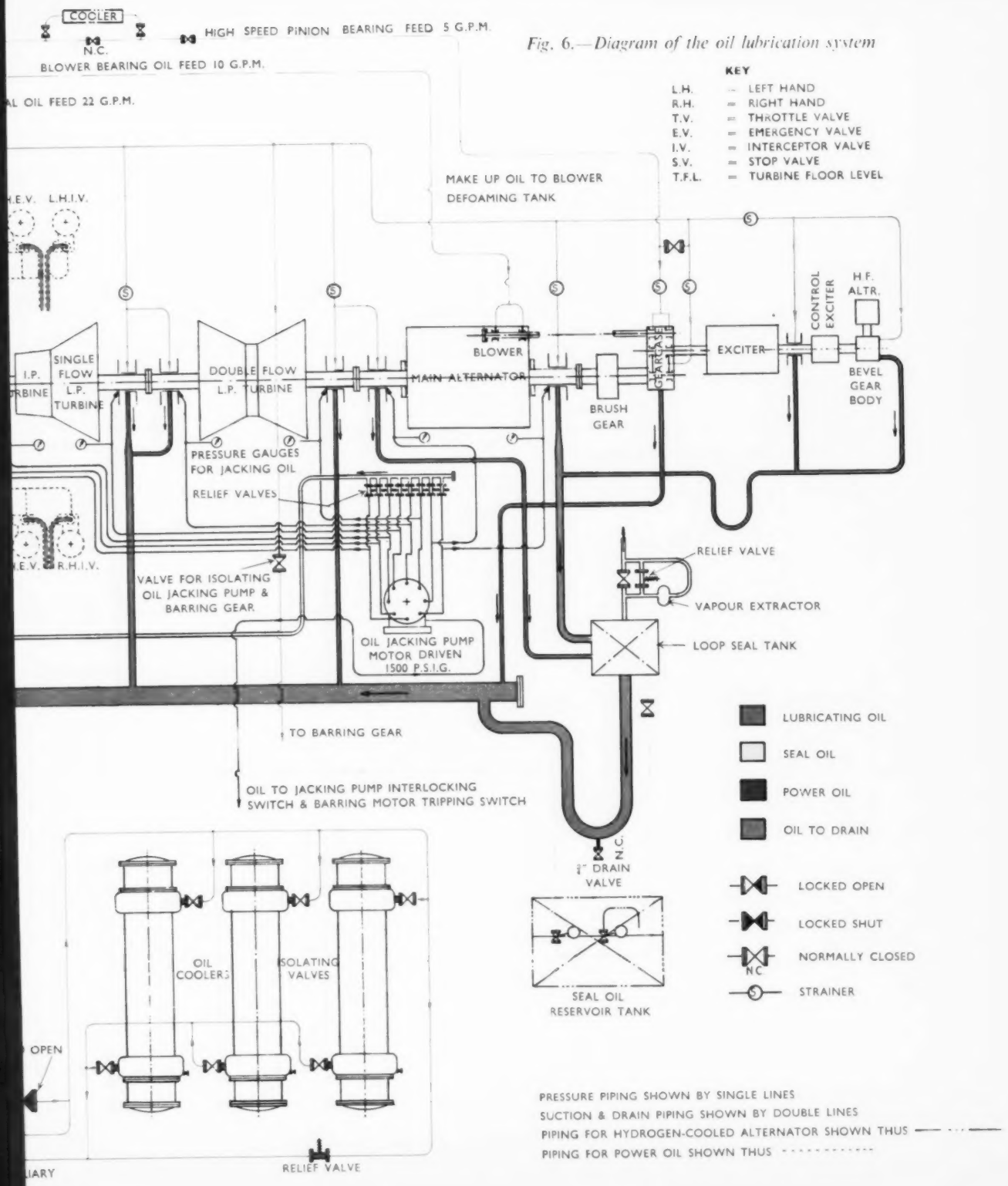


Fig. 6.—Diagram of the oil lubrication system

3. Emergency governor to operate all steam valves on overspeed and thus keep the speed of the turbine well below the safety limit.

Nos. 1 and 2 together have been designed to keep the speed of the turbine below the setting of the emergency governor under all degrees of load rejection and to enable the turbine to be re-synchronised and loaded with the least possible delay.

Speed-sensitive Governor

The initiating signal is given by a centrifugal device driven through gearing from the turbine main shaft. The weights of the device are connected by levers through a cross-shaft and forked lever to two primary relays which control the main throttle valves and the interceptor valves respectively. These convert the movement of the centrifugal device into an oil pressure signal inversely proportional to speed for normal rates of change, i.e., a rise in speed produces a reduction in oil pressure, but the design incorporates a derivative control which increases the rate of oil-pressure-change/speed-change when high accelerations occur, e.g. under load rejection conditions.

The oil pressure signal controls the opening of the throttle and interceptor valves by means of their secondary relays and servomotors. The primary relay bodies have a screwed portion which moves them vertically when they are rotated by the speeder gear handwheel or motor. This changes the opening of the steam valves, thus producing a load or speed change.

Such an arrangement minimises the weight of the movable parts of the governor and makes more rapid action possible on overspeed. The meshing of the speeder gear wheels is such that a fixed sequence of steam valve operation is obtained. Handwheels are provided on the throttle and interceptor valves to enable each one to be closed separately for purposes of on-load testing.

The vacuum unloading gear, which unloads the machine on a fall of vacuum, consists of a regulator connected hydraulically to an oil pressure transmitter which is fitted with switches connected to the speeder gear motor. The boiler-pressure unloading gear also has switches connected to the speeder gear motor and is arranged to unload the turbine on a fall of boiler pressure within adjustable prescribed limits, but will not reinstate load upon recovery of boiler pressure.

Secondary Governor

A specially designed governor having a very rapid response is used to keep the speed of the turbine below the operating point of the emergency governor on load rejections.

An electric signal is supplied to a magnetic amplifier controlling torque motors operating actuator valves coupled hydraulically to large oil-dump valves on the servomotors of each throttle valve and interceptor valve. On loss of this signal, i.e. loss of load, the torque motors are energised, the dump valves open and the steam valves are closed rapidly by springs.

Provision for on-load testing is covered by a selector switch on the secondary governor, which allows each of the actuating torque motors to be energised separately to check the operation of the actuators and dump valves.

Emergency Governor and Trip Gear

Twin emergency governors are fitted to the shaft of the H.P. turbine and are arranged to operate and shut the emergency steam valves in front of the H.P. and I.P. turbines should the speed exceed normal by a predetermined amount. In cases of emergency, therefore, steam is cut off separately from the H.P. and I.P. cylinders. At the same time the portion of the servo-cylinder below the piston in each oil servomotor is opened to drain, thus allowing the springs to close the main throttle valves and the interceptor valves.

The trip gear can also be released by hand-operation at the turbine, remote operation from the control room, or, electrically, by the low vacuum trip. In the event of failure of oil pressure, the trip mechanism on the H.P. turbine stop and emergency valves and the I.P. turbine emergency valves will automatically operate to close the valves. The tripping gear is re-set by hand.

Vacuum Unloading and Trip Gear

The exhaust end of the machine is automatically protected against excessive temperature and internal pressure if loss of vacuum should occur. The vacuum unloading gear provided gradually unloads

the machine by direct action on the governing gear, commencing to unload when the vacuum has fallen to 23 in. Hg, and continuing until, at 17 in. Hg, all load has been removed.

A low-vacuum trip is provided which, in the event of continued fall in vacuum to 15 in. Hg, will trip the main stop valves, I.P. emergency valves, main turbine trip gear, and circuit-breaker, thereby shutting down the set.

In the remote contingency of these two safety devices failing to operate, further protection is afforded to the condenser by the provision of relief diaphragms, one on the top of each exhaust hood. Each consists of a lead sheet supported on the vacuum side by a plate resting on a grid and clamped round its edge between a guard and the grid. During normal operation the support plate and grid take the atmospheric load, but should the load be reversed by excessive pressure developing in the exhaust space, then the support plate will rupture the lead diaphragm round its edge, thus opening the exhaust space to atmosphere. The diaphragm centre and support plate, after sufficient movement upwards, are retained within the guard by cross pieces, and the escaping steam is directed upwards by the guard.

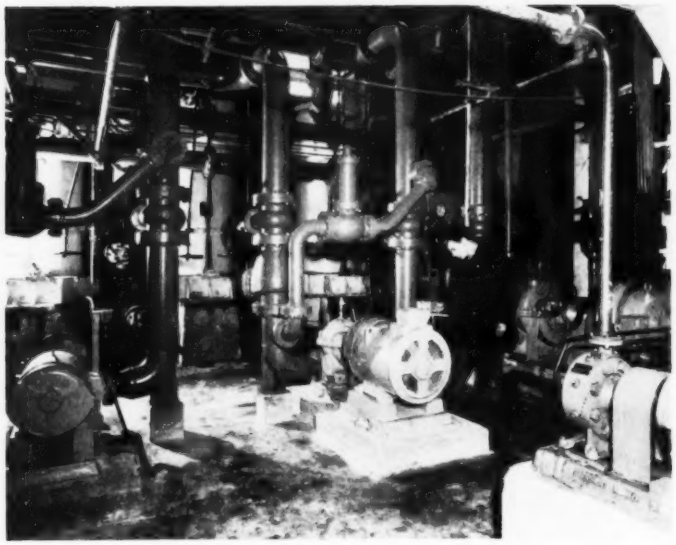


Fig. 7.—Auxiliary lubricating oil pumps in basement

Lubrication

The lubrication system is shown diagrammatically in Fig. 6. It will be seen that the system comprises an oil tank, a main oil pump of the centrifugal type housed in the H.P. pedestal and driven from the H.P. shaft through a flexible coupling, and three motor-driven centrifugal type auxiliary oil pumps (Fig. 7).

The main pump is supplied from the main oil tank by means of jet pumps operating on a re-circulating system which maintains a positive pressure at the pump suction.

The first of the auxiliary pumps is full-duty rated, a.c. motor driven, for use when starting up and shutting down, and in emergencies. It is automatically controlled to come into action when the oil pressure in the main relay system falls below a predetermined value.

The second auxiliary pump is driven by a d.c. motor from the station battery. It supplies oil for lubrication purposes only and is automatically brought into action when the pressure of the oil to the bearing supply main falls below a certain value.

The third auxiliary pump is mainly for use during periods when the electrical turning gear is in operation, and supplies oil for lubrication purposes only. It is a.c. motor driven and is started automatically on falling bearing-oil pressure.

Alarm signals are given if any of these three pumps fails to start automatically.

All the auxiliary oil pumps are driven by ' English Electric ' motors. The oil system also includes an oil-jacking pump and three 50% full duty oil coolers.

Oil from the full-duty auxiliary oil pump is drawn from the tank and delivered through a non-return valve to the distribution box. This is fitted with a relief valve through which surplus oil is

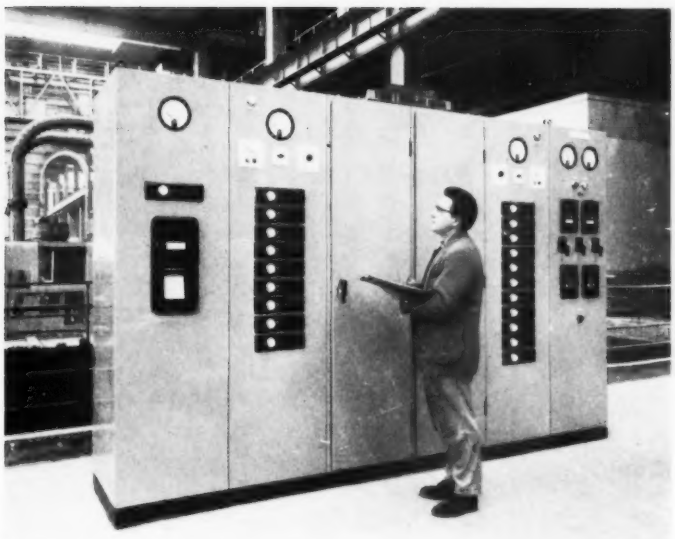


Fig. 8.—Turbine supervisory gear control panel for No. 1 set

returned to the tank. Pressure oil is supplied to the governor relays and servomotors direct from the distribution box.

Oil for lubricating purposes passes through a pressure-reducing valve, which is situated in the distribution box, before continuing to the coolers and thence to the bearings at a pressure of about 15 lb/sq in. Oil drains from the bearings through sight boxes to the bus return pipe, which conveys it back to the oil tank through strainers.

The alternator is hydrogen cooled, and, to avoid possible accumulation of hydrogen pockets in the pedestals and governor control system, a vapour extractor is fitted on the main oil tank and also on the loop seal tank for the oil return from the alternator pedestals. The oil vapour is discharged by the extractor to atmosphere through a pipe extending above the roof of the power station. The extractors are fitted with a by-pass arrangement for use under emergency conditions.

Electrical Turning Gear

Electrically-driven turning gear is provided in order to reduce to a minimum any risk of the turbine rotors distorting and taking a permanent set due to uneven cooling after the turbine has been shut down. The gear is put into operation by hand but is disengaged automatically when the turbine speed exceeds that of the gear.

High-pressure oil jacking is provided at all turbine and alternator bearings, ensuring that each of these journals is supported by a continuous oil film before operation of the electrical turning gear commences and until the journal speed is sufficient to maintain an oil film. Damage to the bearings is thus avoided and the starting effort required from the turning-gear motor much reduced.

Supervisory and Protective Equipment

The turbine and alternator are equipped with a comprehensive range of supervisory instruments to allow the safest and most economic operation during starting, loading, unloading and stopping periods.

The instruments and indicators are mounted on the turbine local instrument panel (Fig. 8) adjacent to the turbine, where they are clearly visible to the operators and indicate and record the following:—

(*a*) Speed of the turbine shaft.

(*b*) Eccentricity of the H.P. and I.P./L.P. rotors, and of the gearbox and outboard ends of the alternator blower drive shaft.

(*c*) Differential expansions of the H.P., L.P. turbine-end and L.P. alternator-end rotors with respect to their casings.

(*d*) Cumulative axial expansion of the turbine casing measured at the steam end.

(*e*) Vibration measured at each of the turbine and alternator pedestals and at the blower gearbox.

(*f*) Indication only of the position of each of the turbine stop valves, main throttle valves, I.P. emergency valves and the I.P. interceptor valves.

(*g*) Megawatt output of the alternator.
(*h*) Temperature at each H.P. steam inlet and H.P. turbine metal casing.
(*i*) Temperature at each I.P. steam inlet and I.P. turbine metal casing.

Alarm signals are operated for the following conditions:—

1. High eccentricities of the turbine and alternator rotors and of the blower shafts.
2. High vibration of any of the turbine or alternator pedestals and of the blower gearbox.
3. Excessive negative or positive differential expansions of the turbine shafts.

In addition to the supervisory instrumentation outlined above, there are also mechanical shaft-eccentricity indicators, a mechanical tachometer, and optical indicators showing the differential expansion of shafts with respect to their casings.

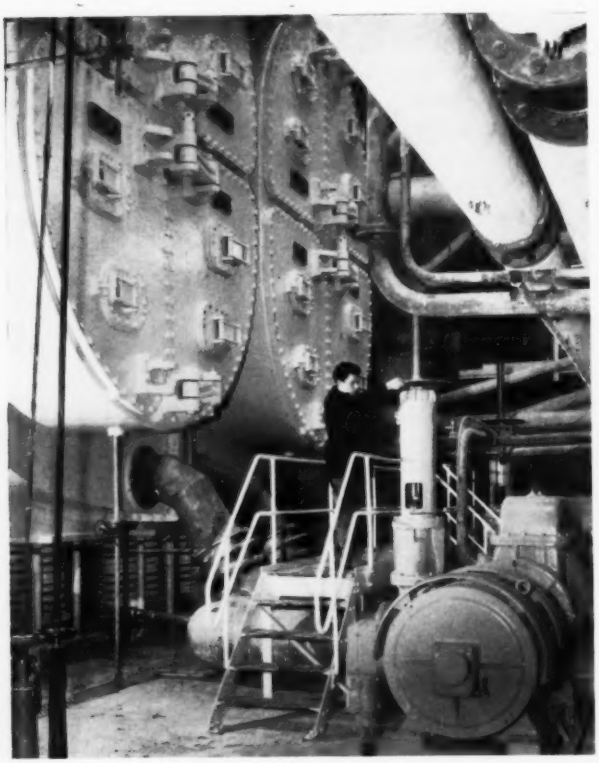


Fig. 10.—*Condenser, with extraction pump driven by* 245 *h.p. squirrel-cage motor in foreground.*

CONDENSING SYSTEM

The diagrammatic arrangement of the condenser and auxiliary circulating water system is shown in Fig. 9.

Condenser

A single shell condenser (Fig. 10) is fitted, having two separate inlet and outlet water boxes, each box being of the two-flow type. One half of the condenser can be isolated on the water side for cleaning during periods of reduced load. For convenience of manufacture, each inlet and outlet water box is subdivided into two sections. Hinge gear is provided and is arranged to accommodate the water box doors on either side of the condenser.

The tubes are arranged in The English Electric Company's standard ribbon formation, so ensuring proper distribution of steam over the entire condensing surface and minimising pressure drop.

The tubes, of 70/30 solid drawn brass 1 inch external diameter, are roller-expanded into the tube plates at the water inlet ends and are fitted with full box packings at the outlet ends, without ferrules. The packings are pre-formed rings of lead foil and fibre, caulked into the stuffing box by a special tool. This gives a watertight joint while still allowing freedom for axial movement of the tube due to thermal expansion. The tubes are slightly bowed to permit complete drainage on the water side.

The condenser shell is of fabricated steel construction, built in four main sections welded and bolted together at site after setting into position.

The condenser is bolted to the L.P. turbine exhaust flange and is carried on spring supports to accommodate expansion and control the loads exerted on the L.P. turbine.

To reduce the number of large holes in the foundation beam under the L.P. turbine, the bled steam pipe to No. 2 L.P.

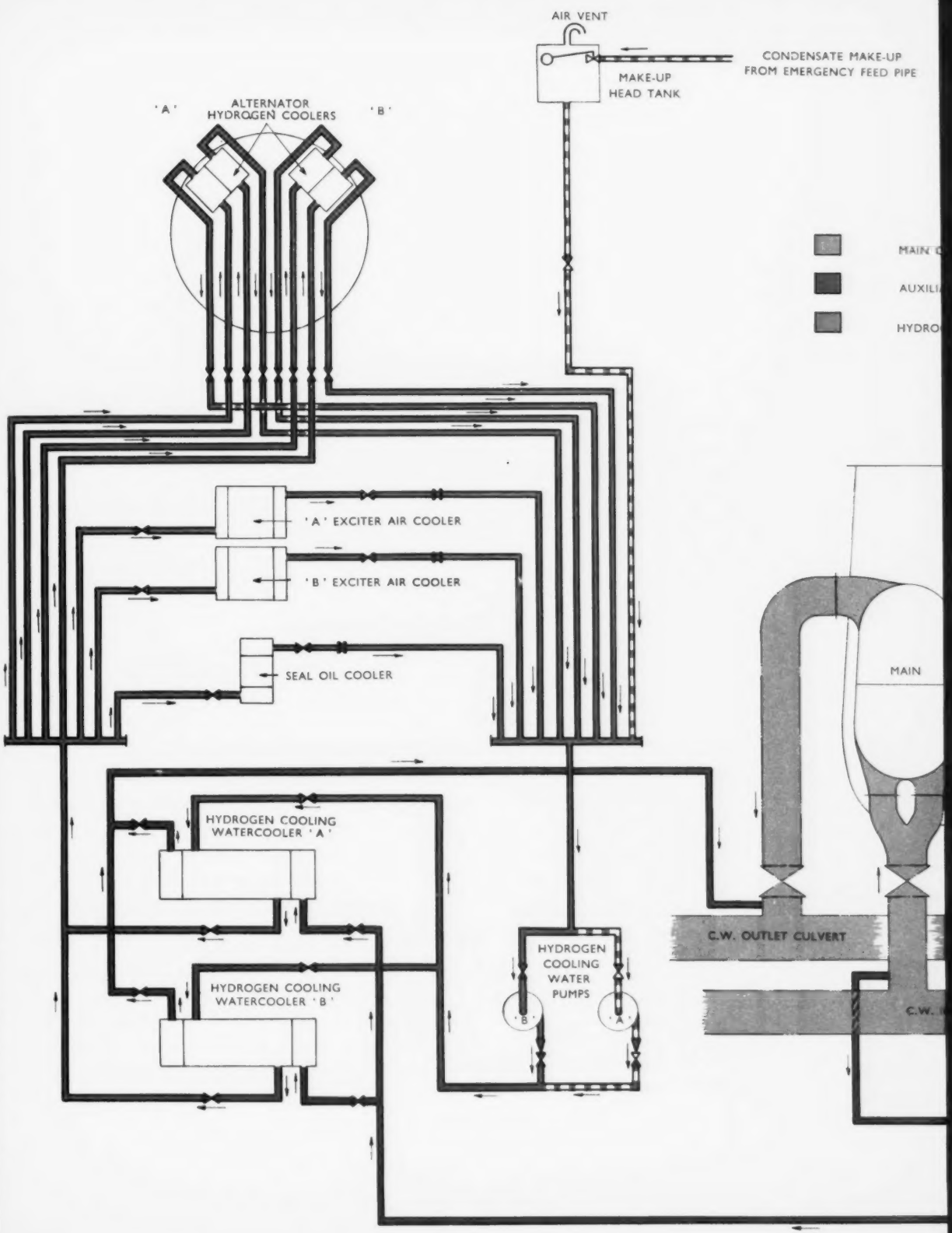
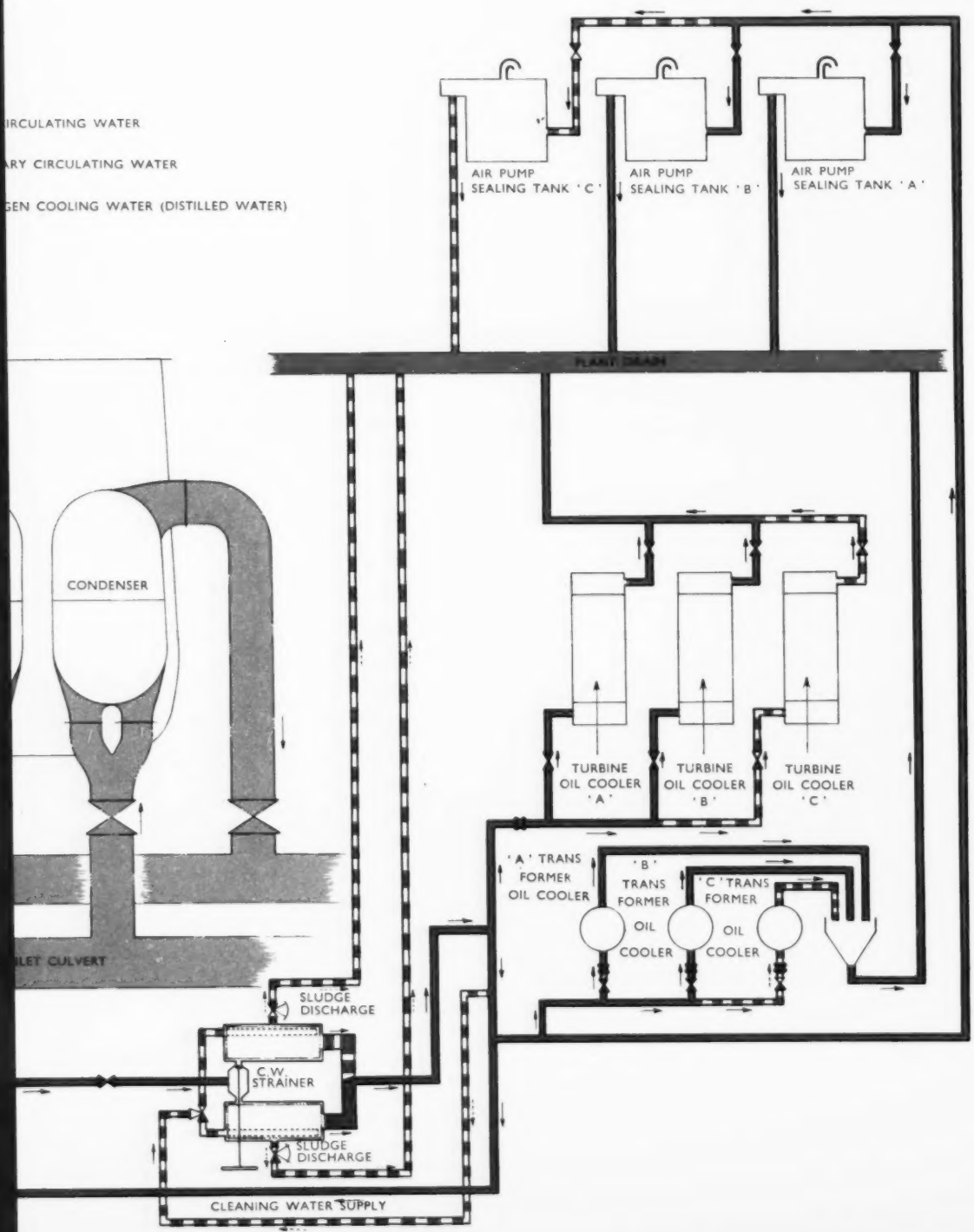
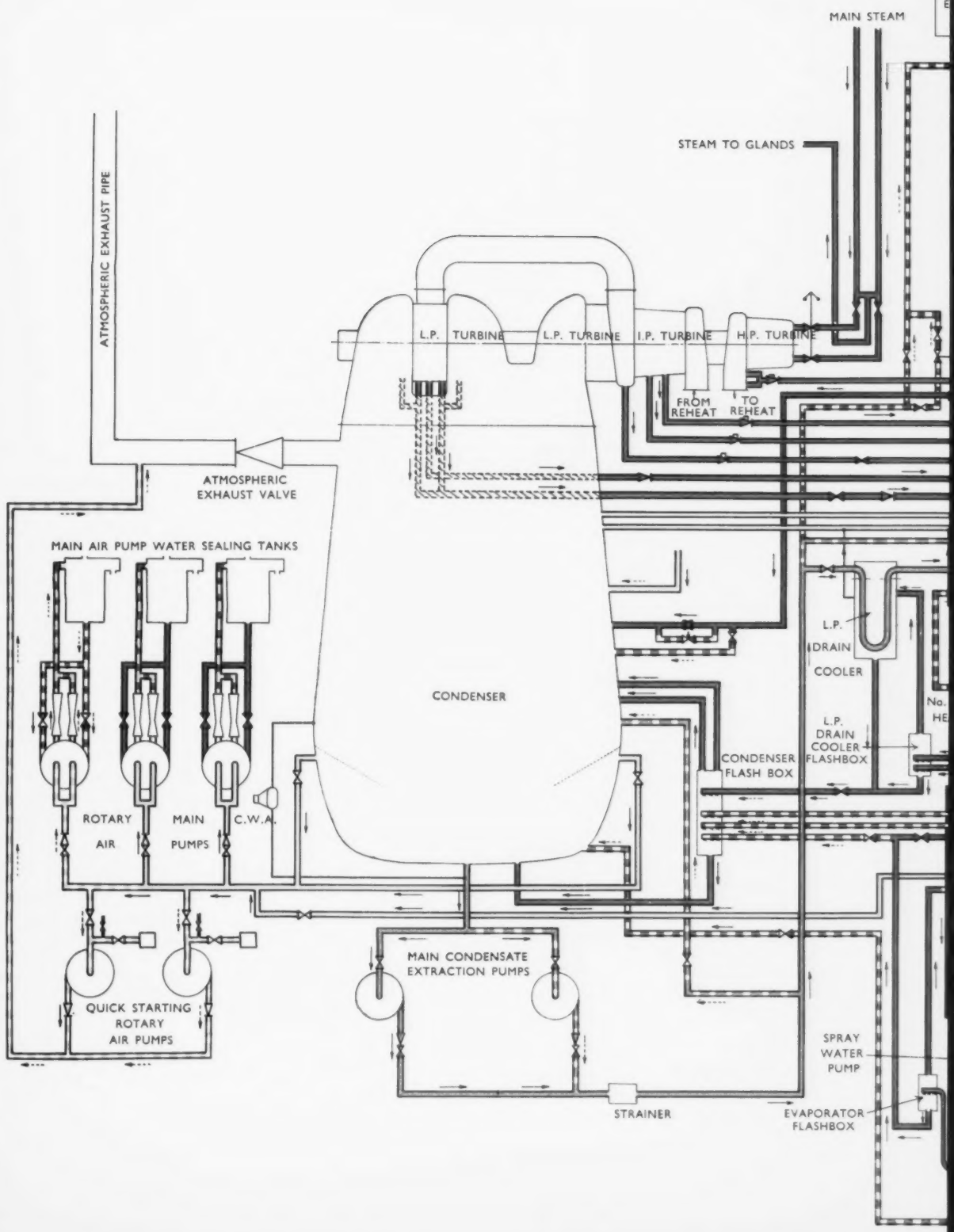

AIR VENT
CONDENSATE MAKE-UP
FROM EMERGENCY FEED PIPE
MAKE-UP
HEAD TANK
'A'
ALTERNATOR
HYDROGEN COOLERS
'B'
'A' EXCITER AIR COOLER
'B' EXCITER AIR COOLER
SEAL OIL COOLER
HYDROGEN COOLING
WATERCOOLER 'A'
HYDROGEN COOLING
WATERCOOLER 'B'
HYDROGEN
COOLING
WATER
PUMPS
'B'
'A'
MAIN
C.W. OUTLET CULVERT

Fig. 9.—Diagrammatic arrangement of condenser and auxiliary circulating water system




MAIN STEAM
STEAM TO GLANDS
ATMOSPHERIC EXHAUST PIPE
L.P. TURBINE
L.P. TURBINE
I.P. TURBINE
H.P. TURBINE
FROM REHEAT
TO REHEAT
ATMOSPHERIC EXHAUST VALVE
MAIN AIR PUMP WATER SEALING TANKS
CONDENSER
L.P. DRAIN COOLER
L.P. DRAIN COOLER FLASHBOX
CONDENSER FLASH BOX
ROTARY AIR
MAIN PUMPS
C.W.A.
MAIN CONDENSATE EXTRACTION PUMPS
QUICK STARTING ROTARY AIR PUMPS
SPRAY WATER PUMP
STRAINER
EVAPORATOR FLASHBOX

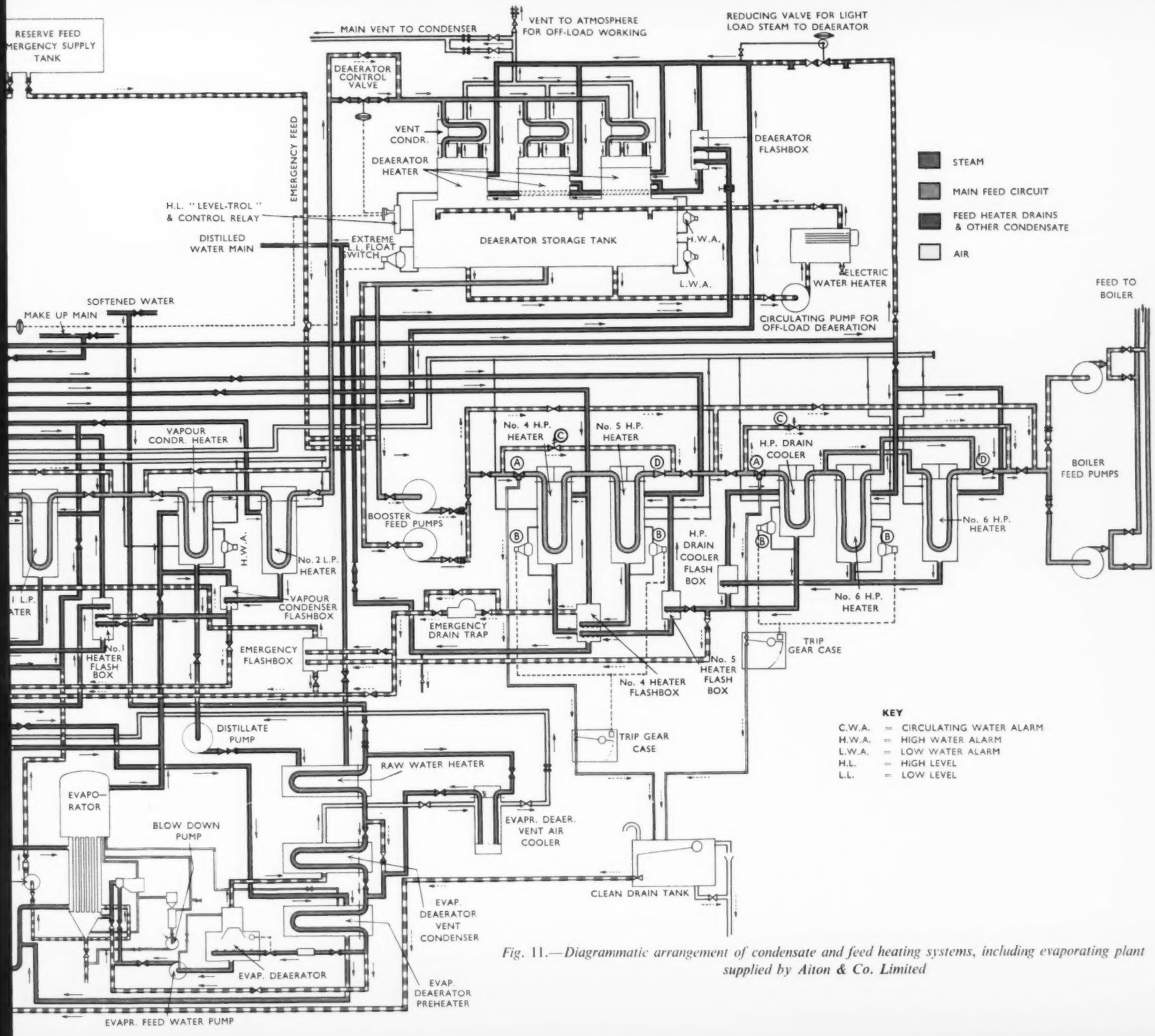


Fig. 11.—Diagrammatic arrangement of condensate and feed heating systems, including evaporating plant supplied by Aiton & Co. Limited

feed heater is taken out through the condenser.

The bled steam pipe is made with the necessary corrugated sections to accommodate thermal expansion effects, and where it passes through the condenser it is encased in an outer pipe which forms part of the condenser structure. The bled steam pipe is covered with moisture-resisting lagging which is protected throughout by a sheet-copper sheath. The lagging prevents heat loss from the bled steam pipe to the condenser, as there is a temperature gradient of about 250°F, at full load, between the bled steam and the condenser steam.

Condensate Extraction Pumps

Two full-duty extraction pumps (Fig. 10) are provided, each capable of dealing with the condensate from the condenser at all loads under normal working conditions.

The pumps are of the horizontal spindle 2-stage 3-impeller design, the second stage having two impellers in parallel, with the first-stage impeller between the two second-stage impellers. This arrangement eliminates first-stage glands which, being under vacuum, are a potential source of air leakage into the vacuum system.

Air Pumps

In order to reduce to a minimum the use of small-bore high pressure and high temperature steam piping, three Leblanc-type rotary hydraulic main air pumps are installed, of which one is a standby, as any two pumps working together are capable of dealing continuously with the air entrained with the steam and with any normal air leakage, and of maintaining the vacuum in the condenser.

Two motor-driven rolling drum rotary exhausters are provided for rapidly evacuating the condensers and vacuum system when starting. When working together these pumps are capable of exhausting the vacuum system from atmosphere to, say, 20 inches Hg in 7 minutes approximately.

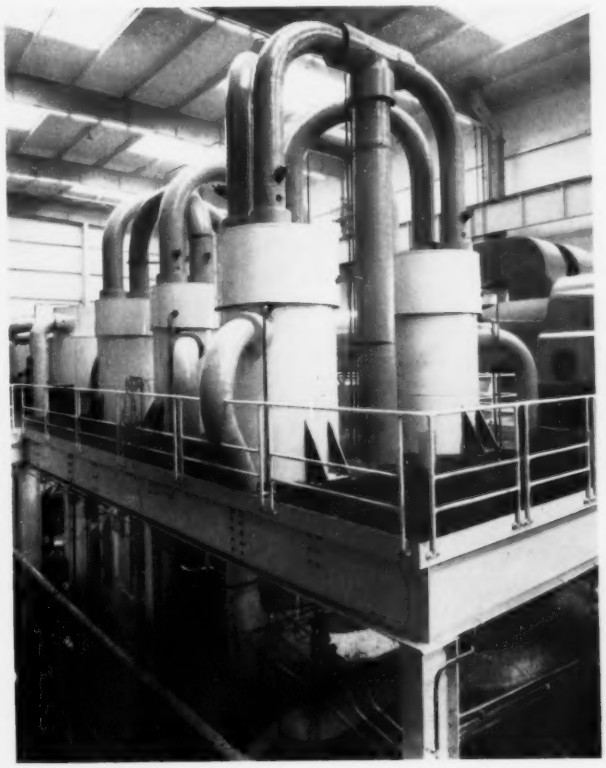


Fig. 12.—The feed-heating and evaporating plant

FEED HEATING SYSTEM

The feed water is heated to a final temperature of 460°F in six main stages of regenerative feed heating.

The feed system is illustrated by the simplified diagram in Fig. 11. Two stages of boiler feed pumping are employed, all the low-pressure heaters being placed between the condensate extraction pump and the first-stage boiler feed (or booster) pump, and all the high-pressure heaters between the booster feed pump and the main boiler feed pump. By this means the high-pressure heaters are designed for only a moderate pressure on the water side, thus reducing their weight.

The extraction pump withdraws condensate from the condenser and delivers it through the low-pressure drain cooler, through the No. 1 and No. 2 L.P. surface

heaters and up to the high-level de-aerating heater of the direct-contact type in which the feed water is sprayed directly into the steam. Feed water than passes down to the booster feed pump and is delivered through No. 4 and No. 5 H.P. surface heaters, through the high-pressure drain cooler, through the No. 6 H.P. surface heater (having two shells in parallel) and thence to the main boiler feed pump suction.

It is well known that optimum efficiency in a non-reheating regenerative cycle is attained approximately when the sensible heat-rises across all feed heaters are equal. A thermodynamical feature of a reheat-regenerative cycle in which the steam for the last heater is bled before the reheater, is that optimum efficiency requires the sensible heat rise in the last heater to be greater than the average sensible heat rise in all other heaters, this ' last heater ratio ' varying from 1·5 to about 2·0, depending on the cycle conditions. This feature renders the last heater surface very much greater than that of the preceding heaters, and in the present instance the last heater is made in two shells to limit the dimensions and weights. These two shells work in parallel, and on account of the large quantity of steam bled to this heater, a high-pressure drain cooler is provided to utilise a proportion of the sensible heat in the last heater drain at the highest possible temperature level.

Steam, extracted from appropriate turbine stages, is passed into the heaters, in which it condenses, giving up its latent heat to the feed water passing through the tubes.

In order to utilise the maximum amount of sensible heat in the condensed steam from the feed heaters, the heater drains are progressively cascaded from stage to stage, the final combined drain from the H.P. heaters being normally returned to the de-aerator, and the combined drain from the L.P. heaters being returned to the condenser. A flash drain cooler is provided in which a large proportion of the residual heat of the combined L.P. heater drain is utilised before the drain is finally passed to the condenser. The sensible heat difference is first flashed-off as saturated steam in a separate flash vessel, and this steam is passed into the drain cooler, which therefore functions as a surface feed heater.

Separate flash vessels are used in all drain cascading stages, thus protecting the heater tubes and drain pipes from erosion and vibration, and, by fitting the orifices in these flash vessels, the drain flashing is done under controlled conditions.

As the turbine stage pressures diminish with diminished turbine load, a point is reached on falling load when there is insufficient pressure difference between No. 4 H.P. heater and the de-aerator to overcome the static head of the latter. The No. 4 heater drain flash box is therefore fitted with an overflow connection which, as the flash box floods on low load, passes water through the emergency drain trap to the condenser flash box.

If extended periods of low-load running are envisaged, the combined drain may be diverted to the emergency flash box, and some of its sensible heat recovered in the No. 1 L.P. heater and drain cooler.

A high efficiency single-effect bled steam evaporating plant is incorporated in the system. Steam is taken from the No. 2 L.P. heater bled steam pipe, and the vapour produced is condensed in a vapour condensing heater interposed between Nos. 1 and 2 L.P. heaters. The resulting distillate is pumped from the vapour condensing heater through the evaporator raw water preheater and thence to the ' polishing ' de-ionisation plant and the make-up manifold to the condensers. When working ' non-evaporating ' the vapour condensing heater acts solely as a drain cooler on the No.2 L.P. heater.

In the event of any heater or group of heaters being out of service, connections are provided for diverting the drain water past it.

The system is arranged in such a manner that all feed heaters, drain coolers and flash boxes are self-draining by gravity to the condenser, to eliminate water-line corrosion when standing.

L.P. Feed Heaters

The L.P. drain cooler, vapour condensing heater and the two L.P. surface heaters are of fabricated construction with steel shells, cast iron water heads and steel tubeplates. The U-tubes are of 70/30 solid drawn brass and are roller-expanded into the tubeplates. On account of the

large size of the bled steam pipes to the L.P. heaters, special belts are provided on these heaters to accommodate the steam branches. Hand by-passes are fitted on the L.P. heaters to enable groups of heaters to be taken out of service.

De-aerator

Due to the high steam conditions, very special consideration has had to be given to de-aeration and the exclusion of oxygen from the feed water. To this end the direct-contact de-aerating heater in three parallel shells is mounted on top of a large storage tank acting as a surge tank. The tank is normally always under pressure so that air cannot leak in, and an alternative bled-steam connection with an automatic reducing valve is provided from the top heater bled-steam pipe to ensure that even on no-load the de-aerator pressure will always be maintained slightly above that of the atmosphere. An external electric circulator heater and pump is provided to maintain a temperature of 212°F in the tank while the set is off-load, and thus minimise absorption of oxygen.

Provision is made in the de-aerator water-level control to pass excess water from the extraction pump discharge up to the reserve feed-water tank. Two pneumatic diaphragm valves are fitted, one at the condensate inlet to the de-aerator and one in the surplus feed-water pipe from the extraction pump discharge to the reserve feed-water tank. These valves have matched characteristics of lift, flow and pressure drop, and are so arranged that on rising level in the de-aerator storage tank, the de-aerator valve closes in and the surplus valve opens out, thus diminishing the flow of condensate into the de-aerator and increasing the flow up to the reserve feed-water tank.

Low-level control of the de-aerator is not included, since it was not justified by the method of operation envisaged for these turbo-generators.

Make-up feed water to make good the system water losses is normally admitted from the make-up main to the condenser through a pre-set needle valve; as steady loads are anticipated, the amount of make-up will be regulated to be slightly in excess of the actual system requirement, thus tending always towards high water level in the de-aerator, the excess passing through the surplus valve up to the reserve feed-water tank. A hand-operated bypass round the pre-set needle valve allows any excessive loss (e.g. heavy boiler blow-down) to be made good.

An electrically-operated emergency feed suction valve is provided on a connection from the reserve feed-water tank to the booster pump suction. Operation of this valve is initiated by a float switch at extreme low water level in the de-aerator. Until this emergency condition prevails, a large volume of de-aerated water is always available to meet feed-pump demands.

H.P. Feed Heaters

The high-pressure feed heaters have fabricated steel shells and forged steel water heads, the lower ends of which form the tubeplates. The U-tubes are of Monel metal, roller-expanded into the tube-plates.

A controlled system of heat-tightening the heater head bolts is adopted to obtain the optimum bolt load under working conditions, i.e. without overstressing the bolt material on the one hand and giving the greatest possible margin of joint load to accommodate sudden temperature changes on the other.

On account of the high temperatures of the bled steam to Nos. 5 and 6 H.P. feed heaters, de-superheating sections are provided in these heaters. The tubes of the last water flow are enclosed in an envelope inside the heater shell, and the high-temperature bled steam is introduced into the top of the envelope. The steam is thus constrained to flow downwards, progressively giving up its superheat until at or about the open end of the envelope it reaches saturation temperature. As the temperature of the feed water passing upwards through the tubes within the envelope is progressively increasing, counterflow conditions exist in the desuperheating section, and the design is such that the feed-water temperature at the heater outlet is equal to the saturation temperature of the bled steam, instead of about 10°F below the saturation temperature, as is usual in an orthodox condensing heater.

The steam leaves the desuperheating section in a saturated condition and the remainder

of the heater surface functions as a condensing heater.

Feed Heater Protective Devices

On large turbine installations the volume of steam stored in the feed heaters and bled steam pipes is necessarily large, and, particularly in the H.P. heaters, the energy of this steam is considerable.

The bled steam pipes to the H.P. heaters and to the de-aerator are provided with special forced closing non-return valves fitted as close as possible to the turbines. These valves are arranged to close on a signal from the secondary governor and also by the turbine trip gear, so preventing back-flow of stored steam into the turbine cylinders, which would increase the overspeed level reached.

Groups of heaters are fitted with automatic bypass valves on the feed side so that in the event of a heater flooding due to a burst tube or choked drain, that heater (or its group) is automatically bypassed on the water side, thus stopping condensation of steam in the heater and the possibility of water passing back along the bled steam pipe.

Referring to Fig. 11, the automatic cut-out valve A is normally held open by the feed pressure acting on the underside of a piston on the valve stem. Rising water level in any heater of the group causes the magnetic float switch B to energise a solenoid which in turn allows a pressure release valve to open, so relieving the feed pressure from the underside of the cut-out valve piston. The cut-out valve then closes by the unbalanced feed pressure, and due to the increasing pressure difference across the bypass relief valve C, the latter valve opens and causes feed water to flow round the automatic bypass. This feed pressure closes the non-return valve D preventing feed water flowing back into the bypassed heater(s). The hand bypasses may then be operated to isolate positively the heaters on the water side, for repair.

Test water connections are fitted to each magnetic-switch float chamber, so that each trip gear may be tested at any time by actually simulating flood conditions throughout the trip gear without interfering with operation of the heaters. The trip gears are fitted with visual and audible alarms to indicate which group of heaters has tripped.

AUXILIARY CIRCULATING WATER SYSTEM

The auxiliary circulating water system is illustrated by Fig. 9. Cooling water for the various auxiliaries is tapped off the circulating pipes to the main condenser, and is first passed through a twin strainer so arranged that the water can be diverted from one strainer element to the other, thus allowing cleaning to be carried out on load. A visible and audible alarm is fitted to indicate excessive pressure drop over the strainers, thus giving warning of the necessity for cleaning.

The cooling water supply to the turbine oil coolers is so arranged that the water pressure at all points in the system is less than the oil pressure, to ensure that in the event of a burst tube or leaking tube end, water cannot pass into the oil system and degrade the oil. To this end, the oil-cooler water service has a completely separate discharge at approximately atmospheric pressure, and is fitted with orifice plates in front of the coolers to limit the water pressure entering the coolers to that necessary only to pass the requisite quantity of water through the coolers and maintain flow to the gravity discharge.

Similar precautions are taken with the transformer oil coolers.

The hydrogen coolers for the main alternator are circulated with distilled water, which has a separate closed system with pumps and coolers. Two full-duty hydrogen cooling water pumps are provided, one of which delivers water through the distilled water cooler(s), through the hydrogen cooler in the alternator and so back to the pump suction. A head tank is fitted at such a height to ensure that the distilled water pressure at the top of the alternator is always above that of the atmosphere, thus preventing leakage of hydrogen in the event of a burst tube or leaking tube end.

Distilled water for the hydrogen seal-oil cooler and exciter air coolers is also taken from the distilled-water cooler outlet and returned to the hydrogen cooling pump suction. The seal-oil cooler and exciter air cooler systems have orifice plates fitted in the pipes to ensure that each service takes its proper share of distilled water.

Two distilled-water coolers are provided, each capable of dissipating 60% of the heat rejected in

Fig. 13.—*Induced draught fan driven by* 2140-1090 *h.p.* 6600 *volt 2-speed squirrel-cage motor of the totally-enclosed water-cooled weatherproof type*

the hydrogen cooler, seal-oil coolers and exciter air cooler at full load. Thus one cooler will be used for loads below approximately 60% of full load, and two coolers for loads above this. A visible and audible alarm is provided to give warning of failure of the distilled water flow.

The sealing water for the Leblanc air pumps is taken from the auxiliary circulating water system. A continuous overflow is maintained from the sealing tank to dissipate the heat generated in the pumps.

BOILER DRAUGHT PLANT DRIVES

Induced Draught Fans

The induced draught fans are driven by 6600 volt squirrel-cage motors of 2140-1090 h.p. at 744-596 r.p.m., which are the largest two-speed motors yet used in Great Britain to drive boiler fans.

The motors embody a composite stator winding in which the high-speed and low-speed coils are wound together, and the respective connections are brought out to opposite ends of the machine. This results in a much more robust winding than can be obtained with the more normal method using separate coils for each speed. In addition, the composite coil allows for improved ventilation of the complete winding.

The motors are of the closed-air-circuit water-cooled type, as shown in Fig. 13, each with two coolers incorporated in either side of the stator frame. The heated air is circulated through the coolers, returning to the motor through ducts built into the bedplate. This arrangement calls for a deeper bedplate than would normally be required, but eliminates the need for elaborate foundations.

The fans are arranged for vane control in conjunction with the two motor speeds, and with the vanes in the open position and the motors running at the lower speed can cater for the maximum continuous rating of the boiler under normal conditions, leaving the higher speed available to meet abnormal conditions.

As these motors are situated out of doors, heaters are fitted to minimise the effect of condensation when stationary.

Forced Draught Fans

The forced draught fans are driven by 6600 volt squirrel-cage duct-ventilated motors rated at 662 h.p. 743 r.p.m. Ventilation is provided by overhead ducting which supplies a filtered air supply to the machines. The heated air is exhausted into the surrounding atmosphere.

The motors are fitted with two pedestal-type bearings mounted on a common bedplate which also supports a fan bearing. These fans also are vane controlled, though in this case the motors are of the single-speed type.

Fig. 14.—One of the alternators on test at The English Electric Company's Stafford Works

Gas Recirculating Fans

The gas recirculating fans are driven by 6600 volt closed-air-circuit water-cooled squirrel-cage motors, rated at 412 h.p., 988 r.p.m. Each motor has a single water cooler mounted on the side of the stator frame and connected to the internal air circuit by side-directed fan shields.

THE ALTERNATORS

All of the five hydrogen-cooled alternators are identical and designed to generate at 16·5 kV when solidly connected to their associated transformers which step-up the voltage to 275 kV. The alternator output is 200 MW at 0·9 power factor, and the rated hydrogen pressure is 30 p.s.i.g.

Direct gas cooling of the stator coils and core and rotor coils is employed, and the ventilation system is similar to that used in the prototype direct gas cooled alternator described in a previous issue of this journal, installed in the Willington 'A' power station of the Central Electricity Generating Board.*

* *Hobley, K. 'The development of direct gas cooling as applied to large turbo-alternators'. E.E. Journal, September 1959, Vol. 16, No. 3, page 3.*

As has been the standard policy of The English Electric Company over the last ten years, where transport facilities permit, the alternator stator is designed as a single unit, i.e. the stator core and windings are integral with the outer frame for transporting in one piece. The weight of the heaviest lift of the stator is 168 tons and transport to site was by road over a route planned with the approval of the Ministry of Transport. Although the shortest route from the Company's Stafford works is only 78 miles, the transporter and its load had to be diverted along a route of approximately 170 miles in order to keep to roads and bridges capable of handling the all-up weight of 218 tons. Fig. 15 shows the stator of the No. 1 alternator before being packed for transport and loaded on to the transporter.

The main components of the alternator are shown in the cross-sectional arrangement in Fig. 16.

It can be seen that, apart from differences in size, the alternator is similar in construction to that in the No. 2 position at Willington 'A' power station, employing a fabricated stator casing of sufficient rigidity for operation at a maximum hydrogen pressure of 45 p.s.i.g.

Stator

The stator core is built with laminations of conventional hot-rolled silicon sheet steel 0·014 inch thick, insulated from each other with Insuline. Axial holes are provided for ventilation and suitably disposed across the core section to provide a uniform temperature distribution. Flexible mounting of the stator core is used to prevent double-frequency vibration being transmitted to the foundations.

The stator winding is arranged with two circuits connected in parallel. Each coil side carries half the rated current and consists of a stack of copper strips forming the conductor, and transposed around a stack of phosphor bronze tubes, using the Roebel method to minimise stray copper losses. The size of the ducts is determined by the quantity of coolant required and the designed pressure drop across all the coolant paths. Fig. 17 shows a section of the stator coil. Adequate sparking and creepage distances to earth are provided at the ends of the coils, and entry to the gas passages is provided by shaped mouldings of fibre glass. All the coil lashings, intercoil packings and slot wedges are of suitable material to withstand the temperatures likely to be experienced in service.

The leads from the stator winding to the terminals are not direct cooled, but are situated at the cool end of the alternator in the recooled gas flow. Direct cooling is, however, employed in the terminals.

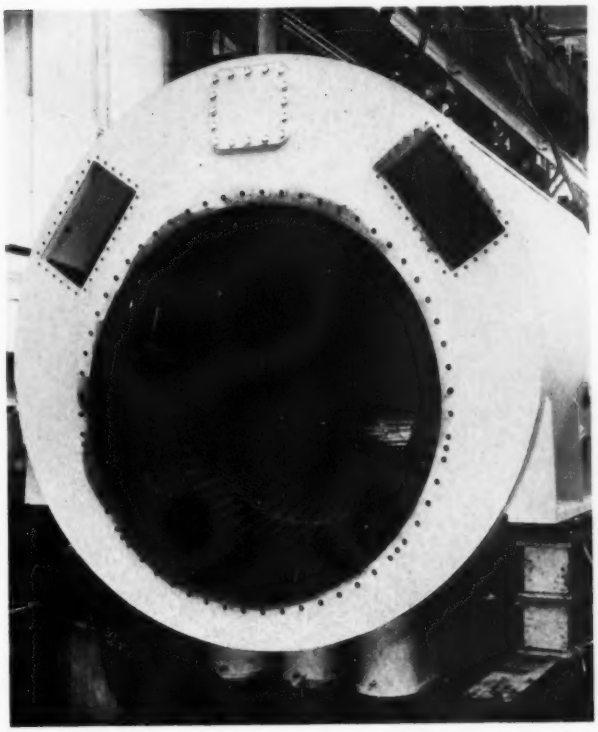


Fig. 15.—End view of alternator stator at Stafford Works

Rotor

The rotor forging is of 3% chromium steel having a minimum yield point of 33½ tons/sq in. The end-winding retaining rings are austenitic alloy steel forgings, the mechanical properties of which are obtained by an expanding mandrel process which ensures that a uniform structure is obtained throughout the material. In addition to ultrasonic examinations, the end-winding retaining rings were tested hydraulically up to a pressure corresponding to a hoop stress of 95% of the specified proof stress.

The rotor conductors are formed from silver-bearing hard drawn copper tube, and samples, taken from a percentage of the tubes used, were subjected to mechanical, electrical and metallurgical tests. Manufacture of the tubes was carried out to a rigorous specification to ensure satisfactory control of hardness, inside and outside corner radii, eccentricity of centre duct and size. Two tubes in parallel form one conductor and there are ten conductors per slot except for the slots adjacent to the pole centres which contain nine. The joints in the winding are brazed and ultrasonic testing is employed to ensure that the brazing is of the required standard. Specially designed extruded copper connections are used to join each pair of tubes to the corresponding pair of tubes in the opposite slots, and to join coils.

The leads from the winding are brought out of the gas-tight enclosure by means of semi-circular section copper conductors in the bore of the forging, the radial

connections to the sliprings and windings being chromium copper studs having chevron-type rubber seals to prevent escape of gas along the bore to atmosphere.

Double-track sliprings, designed to carry the full-load excitation current of approximately 2500 amperes, are situated at the exciter end of the alternator, and are surrounded by a cast aluminium enclosure which contains the brushgear. Air is circulated through the housing by a radial-flow fan, the air being taken from the station atmosphere through a filter and discharged back into the

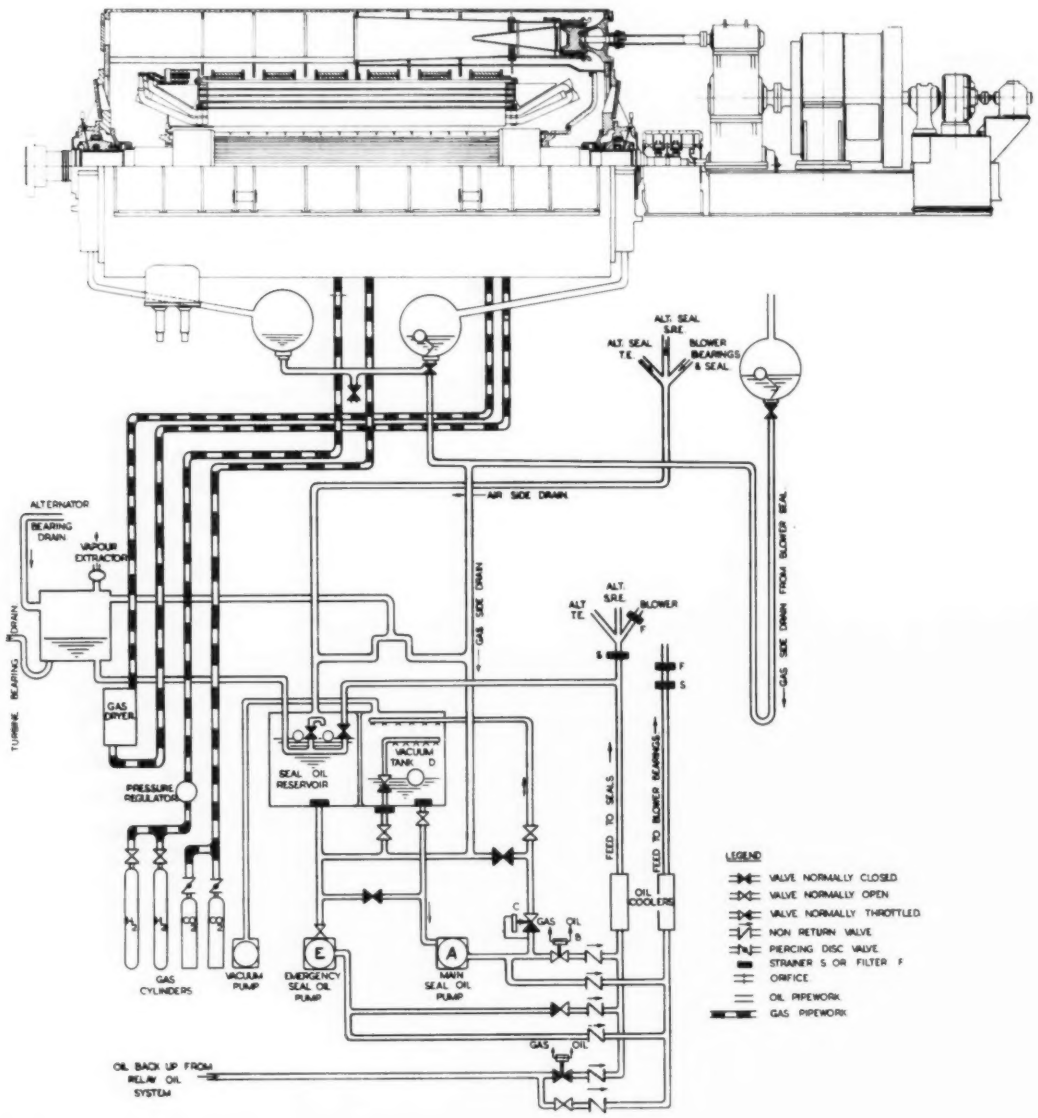


Fig. 16.—Cross-sectional arrangement of the alternator, with gas and seal-oil systems in diagrammatic form

atmosphere in a different location to avoid recirculation of hot air.

As in the prototype direct-cooled alternator, suitable baffle arrangements are provided in the machine to separate the low pressure and high pressure gas flows. The circulation of the hydrogen through the ventilating circuits is also similar to that in the prototype.† Fig. 18 shows the turbine end of the alternator with top half bearing bracket removed.

The hydrogen circulating blower, designed to operate at a normal running speed of 8000 r.p.m., has 5 stages and is driven from a pinion in the exciter gearbox by means of a cardan shaft. Flexible membrane couplings serve to transmit the torque under variations of vertical and axial alignment which can occur between cold and hot conditions of the alternator frame and gearbox. The blower bearings are flexibly mounted in the blower casing. The complete blower is shown in Fig. 19.

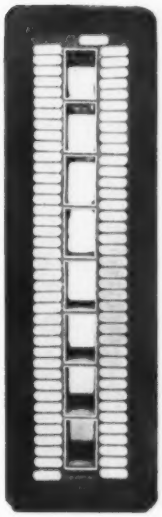


Fig. 17.–Section of stator coil

The alternator rotor is solidly coupled to the L.P. turbine rotor, and provision is made in the design of alternator bearings, gearbox coupling, sliprings, etc. for axial movements of the alternator rotor of up to 0·6 inch which can occur as the result of expansion of the turbine and alternator rotors.

In order to preserve alignment of the blower/gearbox assembly the alternator stator is keyed transversely at the exciter end to prevent axial movement, while at the turbine end allowance is made for axial movement, but transverse movement is prevented by keys engaging with the L.P. casing.

Alternator Shaft Seals

The shaft seals of the alternator are of the patented floating-ring type employing the principle

† *Illustrated by isometric sectional drawing in Fig. 4 of article 'The development of direct gas cooling as applied to large turbo-alternators'. E.E. Journal, September 1959, Vol. 16, No. 3.*

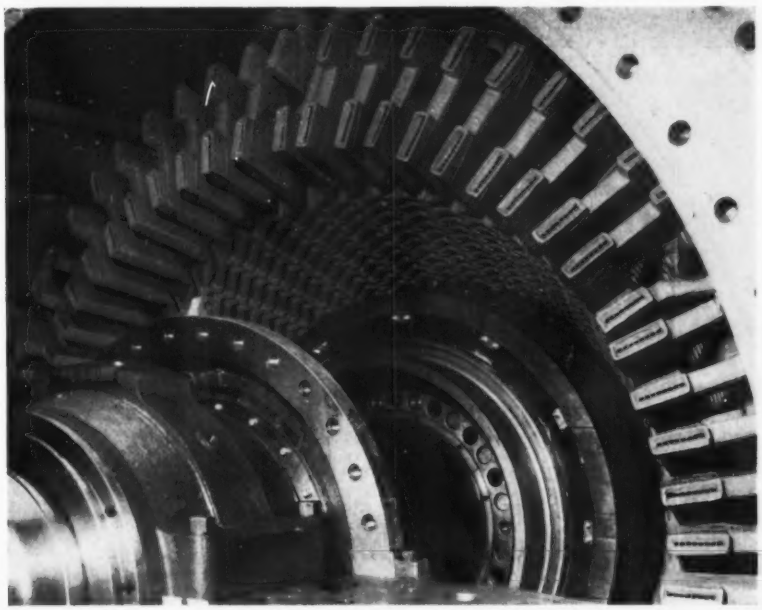


Fig. 18.—Turbine end of assembled alternator with top half bearing bracket removed

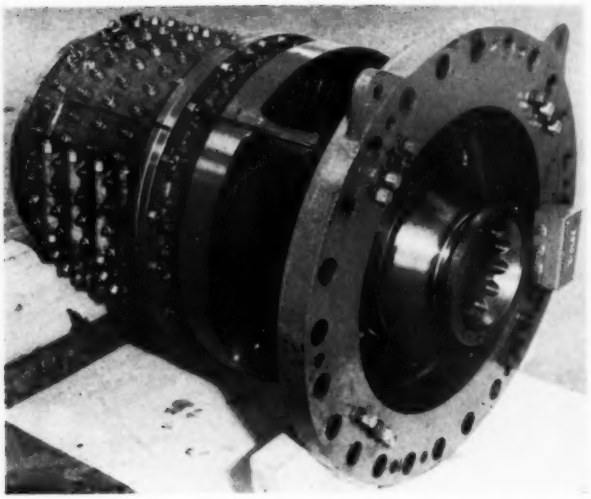


Fig. 19.—Complete blower before assembly in alternator frame

of hydraulic balance, and are mounted in the seal-ring housings bolted to the inboard faces of the bearing brackets. Each of the seals consists of a composite steel ring with white-metalled bearing surfaces surrounding the shaft on the inboard side of the bearings. Oil is supplied to a feed groove half-way across the sealing face at a pressure approximately 12 p.s.i.g. above the machine gas pressure, and flows both ways along the shaft through the clearance space between the rings and the shaft. As long as the oil pressure in the feed groove exceeds the gas pressure in the machine, oil will flow towards the hydrogen side of the seal and prevent escape of gas from the machine. The radial faces of the seals have white-metalled seatings, the face on the air side abutting to the wall of the groove in the seal-ring housing, while the gas-side face abuts on to a diaphragm bolted to a projection on the opposite wall of the groove. A small clearance between the seal rings and the seal housing on the gas side allows the full machine gas pressure to relieve the seal oil pressure on the other side of the diaphragm. In this way the side thrust on the seal is limited. The prototype of this design was thoroughly tested up to pressures on the gas side of 100 pounds per square inch, and the seals have been in regular use on The English Electric Company's alternators since 1955. The seal is shown diagrammatically in Fig. 20.

Blower Seal

The blower seal is of the face type, since the blower is overhung and only one end of the shaft requires sealing. This eliminates the necessity of having to provide a complicated mechanism to follow movement of the blower shaft. The oil is supplied to a feed groove in the face of the seal and is distributed over the seal surface by a number of radial grooves. The seal also acts as a thrust bearing, and when the rotor is stationary or running at low speeds the blower shaft is held up against the seal by means of a surge pad at the outboard end of the blower, supplied with oil from the bearing supply.

Seal Oil Supply

The seals are supplied with normal turbine oil taken from a seal-oil treating unit (Fig. 21)

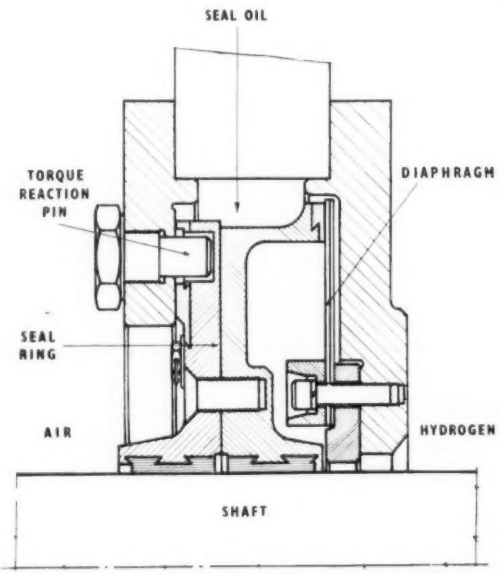


Fig. 20.—Napier balanced-diaphragm alternator shaft seal

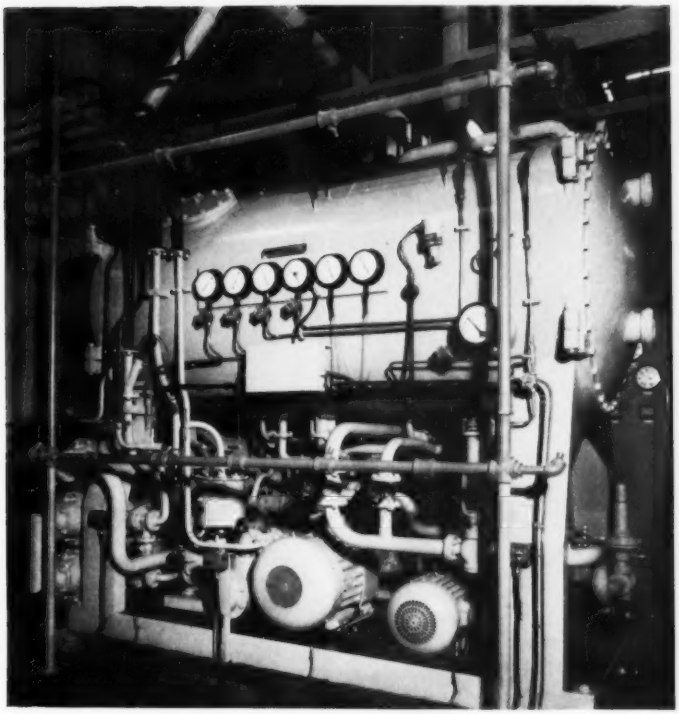


Fig. 21.—*Seal-oil treating unit*

mounted in the basement in the usual way. In order to maintain the purity of gas in the alternator at as high a value as possible, the oil is normally taken from the vacuum tank and circulated by the main pump A, driven by an a.c. motor, shown in the seal-oil supply diagram in Fig. 16. The pressure at the alternator seals is automatically maintained at any desired pressure above the gas pressure in the frame by means of the pressure regulator B. Oil is also supplied to the blower bearings by pump A, and the pressure output from the pump is controlled by regulator C which bypasses part of the pump output through the vacuum tank D. Facilities are provided to take the seal oil from the oil reservoir on the unit, in which case the excess oil is recirculated through the supply pump. This enables the vacuum tank to be isolated from the system when required.

Provision is also made for an emergency supply of oil to be delivered by the pump E, driven by a d.c. motor, should the a.c. motor-driven pump or supply fail.

In the unlikely event of both oil supplies failing, a further supply is available from the turbine relay oil system.

Before the oil reaches the seals it is cooled and filtered.

After passing through the seals and blower bearings, the air-side and blower-bearing drain oil returns direct to the reservoir tank, and the oil from the hydrogen side of the seals drains to settling tanks mounted beneath the alternator, in which any foam is allowed to settle. The gas which is released in the tanks returns to the alternator, and the oil to the vacuum tank via a float-operated valve together with the make-up oil from the reservoir.

The flow of oil from the gas side of the blower is normally very small when the blower is running, but a separate settling tank is provided and the discharge connected via a loop to the main gas-side return to the vacuum tank. The loop serves to prevent flooding inside the blower under certain conditions of operation in air, when a pressure reduction occurs at the inlet to the first stage of guide vanes.

As a safeguard in the event of failure of a shaft seal the alternator bearing drains are taken to the loop seal tank, which is fitted with a vapour extractor so that the drain lines are continually under slight vacuum, and hydrogen is prevented from seeping back into the turbine drain lines.

Gas Supply and Supervision

The usual apparatus for purging and filling the alternator is provided, including syphon-type liquid CO_2 cylinders, gas dryer, hydrogen and CO_2 manifolds, pressure gauges and purity indicator. The latter is of the type which continually samples gas from the frame and by comparing the thermal conductivity with that of pure hydrogen indicates

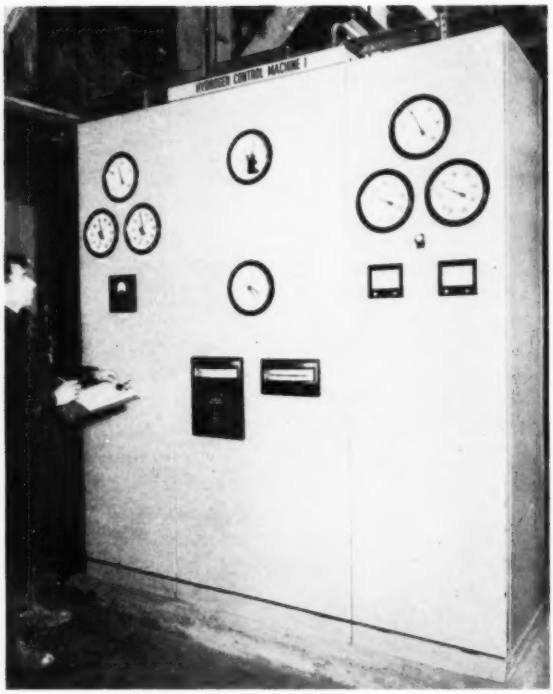


Fig. 22.—Hydrogen control cubicle

directly the percentage purity of hydrogen in the machine. A second gauge in the instrument indicates the percentage of hydrogen or air in CO_2 for use during purging.

The hydrogen control cubicle (Fig. 22), which houses the bulk of the instruments, also contains the intrinsically safe relays which are used in the various alarm circuits. It is designed to comply with the requirements of H.M. Inspectorate of Factories, and all equipment associated with hydrogen is housed in the centre compartment of the cubicle and is ventilated by natural draught through louvres. The connections to this compartment are sealed to prevent hydrogen leaking into other parts of the cubicle.

Exciters

The exciters are driven at 750 r.p.m. They are totally enclosed and ventilated by means of a fan mounted between the main and control exciters, which circulates the cooling air through the exciters and air cooler. Cleanable filters are provided to filter the air before it is returned from the exciter to the cooler. The pedestal is insulated from earth, and an insulated coupling is fitted between the control exciter and a 4 to 1 ratio gearbox which, in turn, drives a high-frequency alternator at 3000 r.p.m. to provide a source of power for the MAEX automatic voltage regulator.

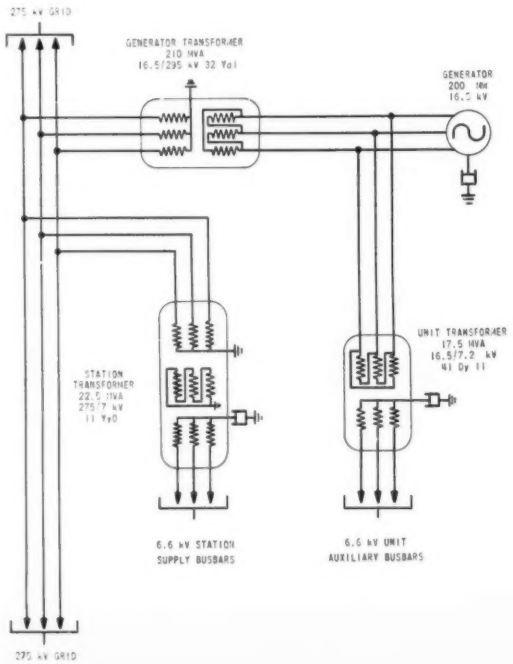
TRANSFORMERS

The diagrammatic arrangement of the three types of transformer installed is shown in Fig. 23.

Generator Transformers

The transformer connected to each alternator is a three-phase unit designed for a

Fig. 23.—Diagrammatic arrangement of transformers



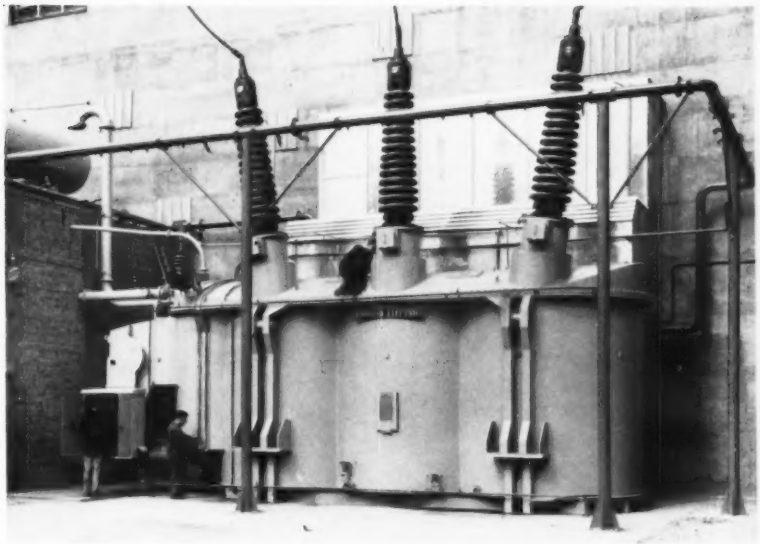


Fig. 24.—One of the generator transformers during installation

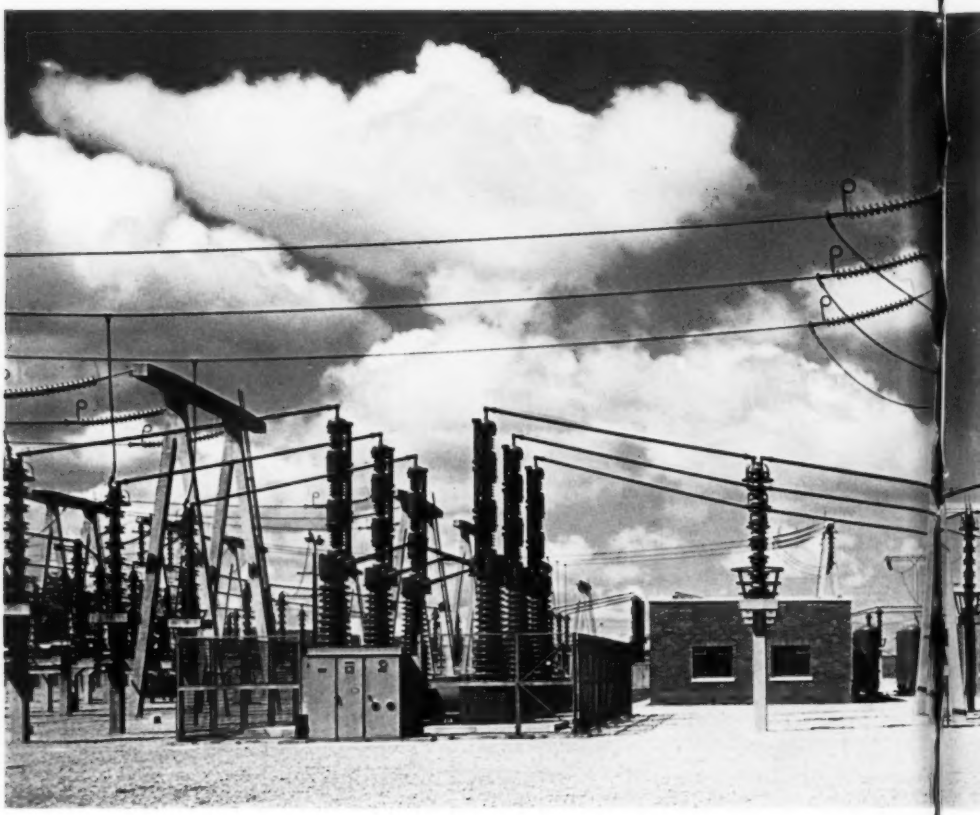
full-load rating of 210 MVA and to step-up the generated voltage of 16·5 kV to the nominal system pressure of 275 kV. Fig. 24 shows one of the transformers during installation.

The high-voltage windings are of the English Electric patented interleaved disc construction, as used for all this Company's high-voltage transformers. With this construction an inherent high series capacitance is obtained, so that under impulse-voltage conditions, such as a lightning stroke, the momentary voltage gradients in the windings are much reduced and the risk of a breakdown minimised. The low-voltage winding, inside the high-voltage winding but insulated from it by a solid barrier of fullerboard, is of spiral construction formed by winding it on a solid Bakelised paper tube, thus giving a mechanically strong base for the whole coil stack. The windings generally are so arranged that the circulation of oil is fully adequate to ensure the lowest possible temperature gradient between the copper and oil, and for eliminating any possibility of excessive local heating. The core is of the five-limb type, which allows a reduction in yoke depth and consequently a reduction in the transformer height, this being a very important factor in transportation to site.

The tank is of the usual welded construction, but specially shaped to increase the rigidity and reduce the transport weight and noise emission. The high-voltage connections are brought out through anti-fog-type oil filled condenser bushings mounted on turrets on the tank cover, the turrets housing ring-type protective current-transformers. The ends of each low-voltage winding are brought out to make a delta connection externally: this is done by using six anti-fog-type bushings per phase, to which the generator connections are made.

The cooling necessary to dissipate the full-load losses is effected by pumped oil circulation through three 50% duty water coolers. They are connected to the transformer tank by large-diameter pipes in which are interposed the main stop valves, pumps and oil-submerged pump motors. The scheme permits any two coolers and any two pumps to be used at any one time, thus leaving one of each as an emergency standby.

Temperature indication is given by two dial-type instruments mounted in a kiosk and connected by capillary tubes to their respective resistive elements in the tank cover. A coil, calibrated to give the same temperature gradient as the main winding, surrounds each element and is supplied from the secondary of a current-transformer, the primary of which is in series with the main transformer winding. The temperature thus indicated follows, with a negligible difference and time lag, the



Part of the Connah's Quay 275 kV substation in the North West, Merseyside and North Wa of th extension and is initially equipped for two feeders, one bus-coupler and two transformers. It has ton

The substation was completely equipped by The English Electric Company. On the right VA transformers are in the centre, and a 275 kV 7,500 MVA air-blast circuit-breaker on the l bac outdoor air-storage receivers.

The contract for extensions to this station has now been received, including three 275 kV 7,500 M cir

Vale of the Central Electricity Generating Board. This is a double-busbar station arranged for future has ...ton feeder circuit and bus-section isolators.

ht ...VA 132/275 kV transformer and parallel isolator with earthing switch. The 275 kV current-... background are the control, relay and compressor rooms, and high-pressure vertically mounted

... circuit-breakers.

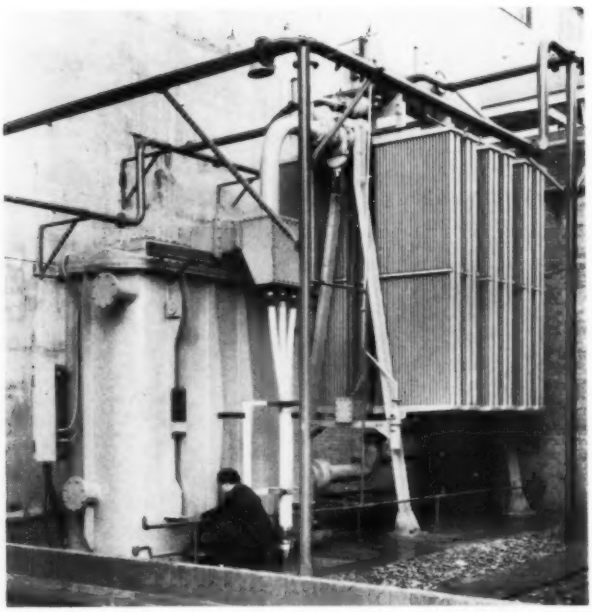


Fig. 25.—A unit transformer

actual winding temperature. The supply from the secondary of the current-transformer can be short-circuited by means of links in the marshalling kiosk, thus leaving the corresponding thermometer to function on oil temperature. Switches incorporated in each instrument are connected to protective circuits so that an alarm is given if the temperature exceeds a predetermined figure. Protection against internal faults is provided by a double-float Buchholz relay situated in a pipe connecting the conservator to the transformer tank.

The transformer terminal voltage is variable over a range of plus and minus 10%, to cover various operating conditions, by means of tappings on the H.V. winding controlled by English Electric on-load tap-changing equipment. A three-phase motor-operated tap-changer is fitted, of the dial selector switch type, mounted at the end of the transformer tank on a pocket containing the mid-point auto-transformer. The tapping range is covered in fourteen steps and the tap-changers are controlled from hand-operated switches in the control room. A direct-reading tap-position indicator is fitted to the tap-changers, and remote indication is also provided in the control room by electrically operated instrumentation.

The control, indication and protective connections are taken to the control room by multicore cables, and a marshalling kiosk is installed immediately adjacent to each transformer for convenient grouping of the wiring from the transformers. The kiosk is divided into several compartments containing the tap-changer isolating switches, relays and the two winding-temperature indicators, the dials of which are visible through a window in the compartment door.

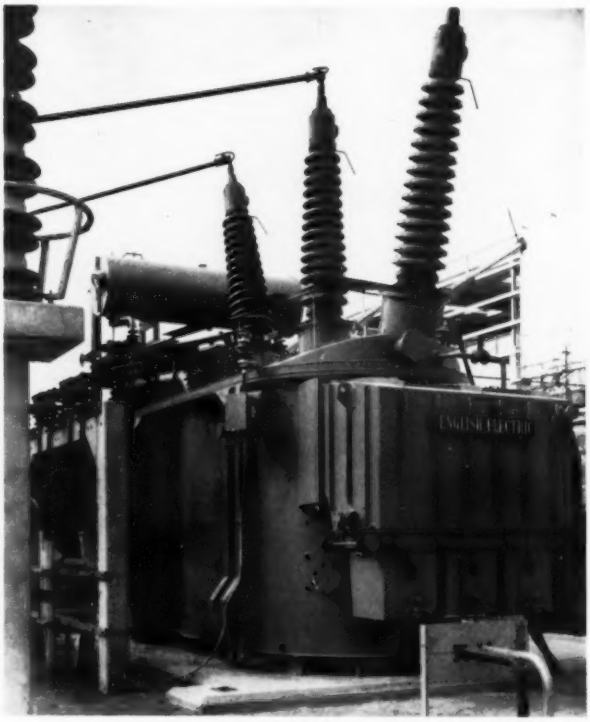


Fig. 26.—One of the two station transformers

Fig. 27.—Class M turbine-house auxiliaries switchboards Nos. 1 and 2

Unit Transformers

Each generator is provided with a unit transformer (Fig. 25), connected to the generator busbars, for supplying boiler feed pumps and other unit auxiliaries. These transformers have a rating of 17·5 MVA and a voltage ratio of 16·5 to 7·2 kV at no-load, corresponding to the full-load supply system voltage of 6·6 kV. As the generator voltage is reasonably constant under normal operation, on-load ratio control is not necessary, but off-circuit tappings are provided to give a range of plus and minus $7\frac{1}{2}\%$ in six $2\frac{1}{2}\%$ steps.

The transformers are of the natural-oil-cooled type, with a bank of elliptical tube radiators, positioned at one end of the tank, through which the oil circulates by convection. The maximum rate of flow is ensured by the cold oil being returned to the tank on a level with the bottom of the windings, thus avoiding contra heads of cold oil at the bottom of the tank, and the outflow coinciding as nearly as possible with the hot-oil level at the top of the tank, so that the total available difference in head is fully employed.

The protective devices incorporated include a Buchholz relay and two winding-temperature thermometers.

Station Transformers

Two station transformers (Fig. 26) connected to the grid system supply the station services and, under emergency conditions, the load normally taken by the unit transformers. Each transformer has a rating of 22·5 MVA and a voltage ratio of 275 to 7 kV at no-load, corresponding to the normal supply system voltage of 6·6 kV at full load. Both the high voltage and low voltage windings are connected in star, and a delta-connected tertiary winding is incorporated for suppression of third harmonic waveforms which would otherwise appear in the output voltage.

Since the supply voltage is liable to fluctuations, on-load tap-changing equipment is fitted to provide a range of plus and minus 10% in fourteen steps of 1·43%.

These transformers are of the same general construction as the generator transformers, with the exception of the cooling arrangements, which are of the same type as those used for the unit transformers.

415 VOLT AUXILIARY SWITCHGEAR AND FUSEGEAR

Station Services

Services common to the station are fed from 2 turbine-house boards, 2 boiler-house boards, 4 coal-handling boards and 2 ash-handling boards, all of the Class M air-break cubicle type with a rating of 31 MVA at 415 volts.

These boards are arranged in pairs, the two turbine-house boards shown in Fig. 27 being typical. By means of selector isolators the busbars of each pair of boards can be connected together or separately to either of two transformers stepping

down from the 6·6 kV station busbars, which are fed by the station transformers described in the previous section and can be interconnected with the unit-transformer busbars.

In addition to controlling the supply to distribution and motor-control boards, the Class M switchboards also control direct-on-line started motors ranging from 92 to 450 h.p.

Unit Auxiliaries

The 415 volt auxiliary switchgear directly associated with the five 200 MW generating sets comprises 10 boiler boards and 5 unit boards, all of the M class as for the station services. These boards are fed through step-down transformers from the 6·6 kV unit-transformer busbars. They control the supply to distribution and motor-control boards for the boiler and turbine essential auxiliaries, and also direct-on-line started and induction-regulator controlled motors of up to 440 h.p. Fig. 28 shows one of the unit boards.

Class M Switchboards

The Class M switchboards provided for the 415 volt station services and unit auxiliaries are of the fully enclosed and interlocked steel cubicle type, incorporating air-break circuit-breakers with ASTA certified short-circuit ratings.

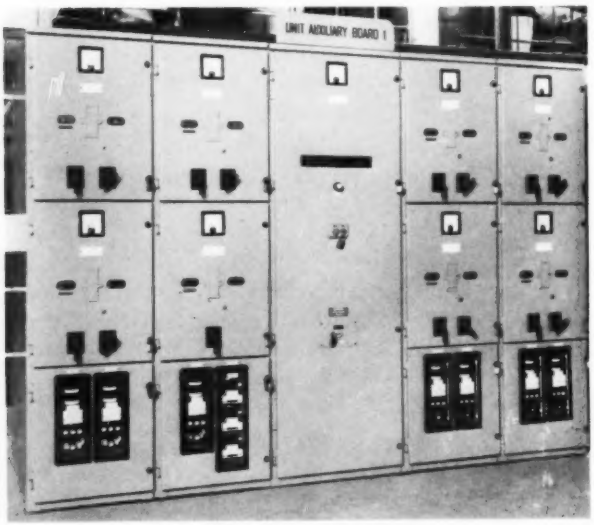


Fig. 28.—A Class M unit-auxiliary switchboard

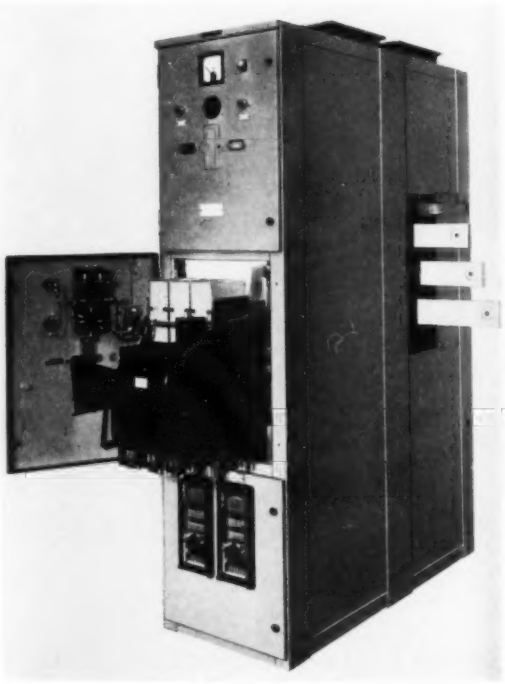


Fig. 29.—A double-tier Class M cubicle, with lower circuit-breaker withdrawn for inspection

The cubicles have either a single- or double-tier arrangement, and the circuit-breakers are isolated horizontally with the door closed, or completely removed from the cubicle on extensible rails for inspection, as shown in Fig. 29. Automatically operated shutters, which can be individually operated for maintenance purposes, screen the cable and busbar isolation connections when the breaker is withdrawn. The isolators are of the self-aligning cluster type, each cluster providing several contacts in parallel, and the passage of current tends to increase the already high contact pressure, thus giving excellent performance on heavy through-fault currents, with no tendency to blow-off.

The circuit-breakers may be either hand or solenoid operated. The contact system consists of three single-pole units employing main and arcing contacts of the butt type. The frame of the breaker is insulated from all current-carrying parts and is earthed. It contains the mechanism linkage, which is so arranged that under fault conditions most of the electromagnetic forces are directly transmitted to the frame, and only a small portion to the closing and tripping linkage. The electrical operation of the circuit-breakers can be tested when isolated, as the control circuit is not broken.

The consistently short arcing time of the circuit-breakers ensures the minimum contact erosion, and so makes the unit particularly suitable for motor control or other frequent duty. The opening movement is arrested by a patented catch which momentarily latches the mechanism at the end of the opening stroke, to prevent rebound. An arc chute containing a series of suitably spaced steel plates is provided for each phase, these splitter plates, due to magnetic interaction with the arc field, assisting in drawing the arc rapidly upwards into the chute, where it is broken up and cooled to extinction.

Earthing of the cable or busbars can be effected through the circuit-breaker. The neutral link is in the form of a sliding isolation contact, which simplifies operation, avoids an open-circuited neutral, and has a through-fault-current rating equivalent to 31 MVA. The neutral-link operating handle is in the circuit-breaker compartment and therefore available only with the breaker isolated. Automatic closing of the neutral link can be provided.

Fig. 31.—Compartment of 'Superform' switchboard, containing fuse-switch and contactor

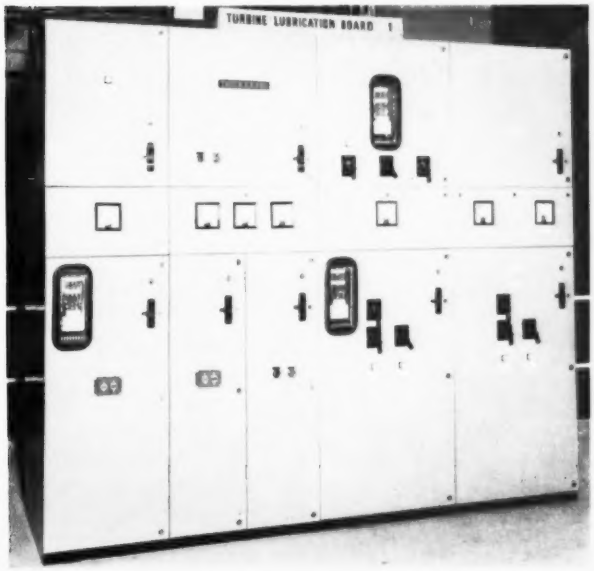


Fig. 30.—'Superform' auxiliary switchboard for turbine lubrication plant

Superform Switchboards

The numerous 415 volt distribution and motor-control switchboards for the station services and unit auxiliaries, fed from the Class M switchboards previously described, are of the Superform steel cubicle type incorporating the required combinations of

high-rupturing-capacity cartridge fuses, circuit-breakers, contactors and other equipment, for the individual circuits controlled.

One of these boards, controlling turbine lubrication-plant motors, is shown in Fig. 30, and Fig. 31 shows a typical compartment for this class of board. A particular and exclusive feature of the Superform equipment is that each contactor is in series with an ' on-load ' fuse-switch. This enables stalled rotor current to be interrupted should the contactors weld in, as occasionally happens in service.

The circuit-breakers, when provided, are of the same type as those included in the Class M switchboards. The cartridge fuse links are ASTA certified for a rating of 35 MVA at 440 volts.

The Control of High-Speed Coil Preparation Lines of the Tight-Line Type

By J. T. BENTLEY, M.Sc.(Tech.), A.M.I.E.E., Metal Industries Division.

The December 1959 issue of this journal contained an article describing the tinplate flow-melt equipment at the Velindre Works of the Steel Company of Wales. The present article refers particularly to the coil preparation lines at the same works.

THIS ARTICLE outlines the problems involved in the control of high-speed coil preparation lines, with particular reference to the two lines installed at the Velindre Works of The Steel Company of Wales.

The function of each line is to prepare the coils of steel strip for electrolytic tinning ; the coils are received from the temper mill and are inspected, side trimmed and built into larger coils.

Although the above processes could be carried out on the tinning line itself, it is generally found more economical to use a high-speed coil preparation line as a separate process, for the following reasons :—

1. Whilst side trimming at the entry end of the tinning line is possible, it would have to take place at the relatively slow speed of this line and would cause the trimming line to be shut down during the relatively frequent knife changes.
2. In order to weld the relatively small coils together on the tinning line it would be necessary to slow down the process section frequently.
3. Side trimming at the end of the tinning line is entirely feasible from a mechanical standpoint, but with the disadvantage of tinning the side scrap, which wastes tin and renders the scrap unsuitable for charging into an open-hearth furnace without de-tinning.

THE VELINDRE LINES

The coil preparation lines installed at the Velindre Works are shown in Fig. 1, the two lines being situated side by side. The mechanical equipment was manufactured by the Head Wrightson Machine Co. Ltd., The English Electric Company provided the electrical drives and control equipment, and McLellan & Partners acted as the consulting engineers in co-ordinating the overall project.

The lines are designed to deal with 36,000 lb coils of 72 inches maximum diameter and 16 to 38 inches width, the strip thickness ranging from 0·006 to 0·024 inch. Maximum line speed is 4,000 ft/min, which as far as is known is the highest speed ever attained outside the United States of America for lines of this type.

The diagrammatic layout of each line is shown in Fig. 2. Strip is fed from the pay-off reel through the idle rolls which guide the strip into the gauge stand and pinch rolls. It then passes through the down-cut shear and seam welder. The gauge enables the operator to detect any off-gauge material, which is then cut out with the air-operated shear and passed overhead by means of a conveyor to the reject coiler at the end of the line. The welder joins the end of the preceding coil to the start of the next. Prime material passes through the bottom pinch rolls to the side trimmer, burr masher rolls and on to the prime coiler.

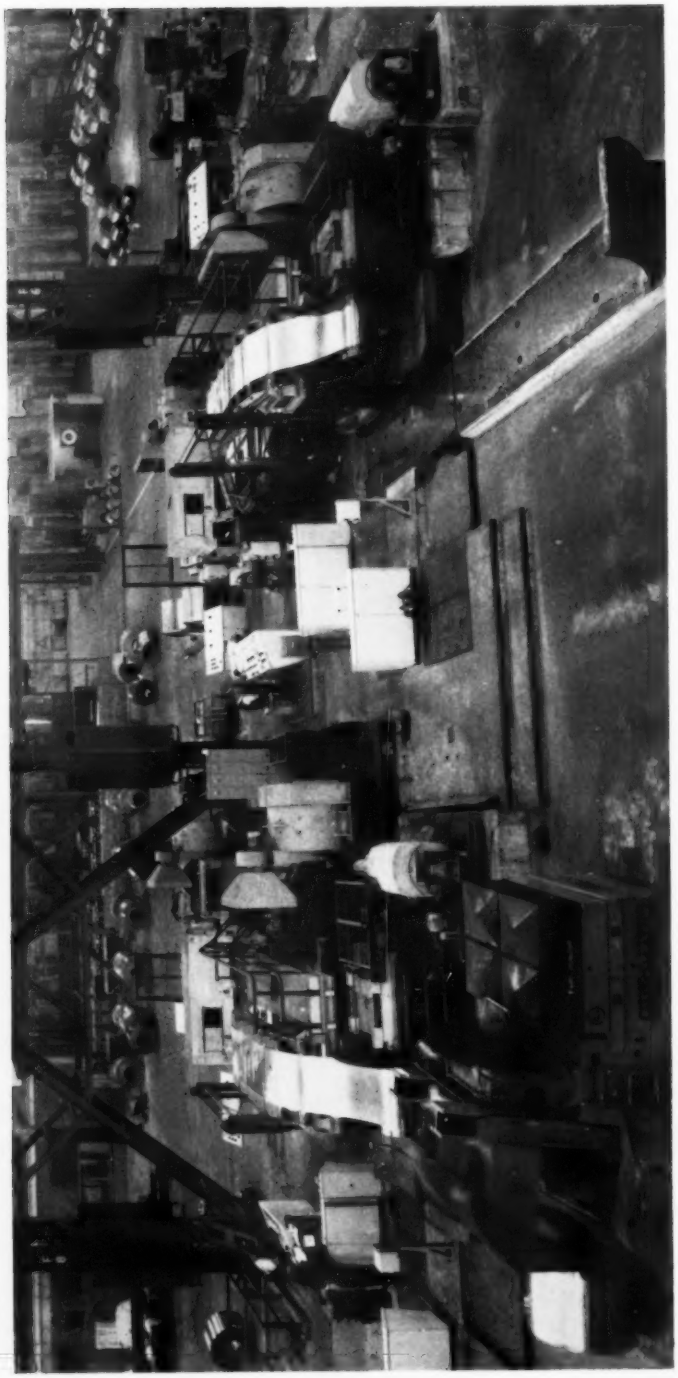


Fig. 1.—The two coil-preparation lines at the Velindre Works of The Steel Company of Wales

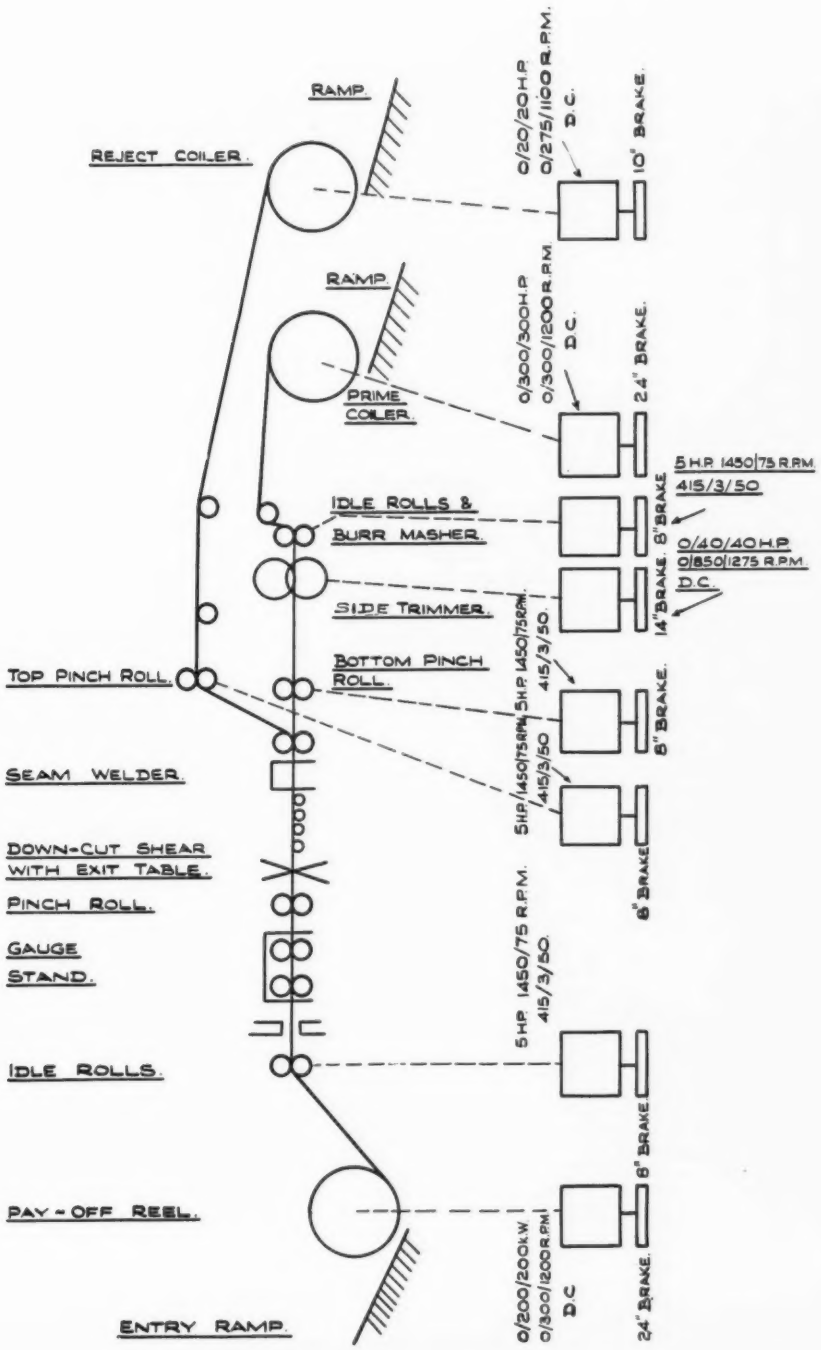


Fig. 2.—Diagrammatic layout of coil-preparation line

GENERAL CONSIDERATION OF CONTROL FEATURES

Before discussing in detail the actual circuitry used on the Velindre lines it will be advantageous to consider briefly the general problems involved in the design of a control scheme for this type of line.

Line Speed Control

The control scheme must ensure that the line runs at the desired speed during the whole process time, and must also maintain a constant pre-set tension in the strip under all operating conditions.

The problem is complicated by the fact that the only two machines having any control over the strip behaviour are the pay-off reel drag generator and the coiler motor. These machines can only control the strip through their associated coils, whose diameter is continually changing throughout the process. Due to coil diameter variations the speed of each motor must be varied in inverse proportion to the diameter change, if constant strip speed is to be ensured. Furthermore, if the strip tension is constant, the torque of the machine must also vary in proportion to the coil diameter. These considerations suggest that some kind of field control is required to establish the necessary control features. Some lead to the method of approach can be gained from the simple mathematical analysis given below.

For a mandrel coiling or uncoiling strip under constant tension at constant strip speed the following relationships hold :—

1. The mechanical power supplied to the mandrel (tension $\times$ strip speed) is proportional to the electrical power generated or used (generated e.m.f. $\times$ current = E.I.)
2. The mandrel speed (strip speed/coil diameter $\times\pi$) is proportional to the motor speed, which is proportional to E/ϕ.

$$\therefore S \times T = K_1 E \times I \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$\text{and } S/D = K_2 E/\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $K_1 K_2$ are constants.

Combining the above

$$S/E = K_1 I/T = K_2 D/\phi \quad \ldots\ldots\ldots\ldots \quad (3)$$

T = strip tension
S = strip speed
D = coil diameter
E = generated e.m.f.
ϕ = machine field flux
I = machine current

The above relationship indicates that for each mechanical variable of the strip being coiled there is a corresponding electrical machine variable which can be used to control it, provided it can be arranged to have some electrical function corresponding to the required strip speed. This can be achieved by feeding the whole line from a single generator whose voltage can be used to give the main voltage component for the individual d.c. drives, and can also be used as a reference for the line speed control.

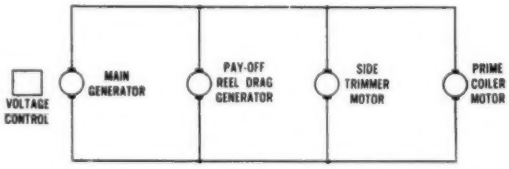


Fig. 3.—Basic circuit of electrical machines

Fig. 3 shows this arrangement for the pay-off reel motor, side trimmer motor and prime coiler motor ; the reject reel motor is fed from its own separate generator and will be dealt with separately.

E.M.F. Control for Pay-off Reel

Since the strip is to be maintained under tension throughout the process, it is evident that the pay-off reel machine must be arranged to act as a drag generator, and therefore provide a braking torque for the coiler motor to pull against.

Returning again to the foregoing mathematical relationship, equation (1), it can be seen that if the generated e.m.f. is maintained proportional to strip speed, the required tension can be obtained by control of the machine current.

As the strip speed is proportional to the main generator voltage, the above statement suggests

that the back e.m.f. of the machine should be held equal to the main-generator supply voltage.

From the generator electrical equation

Supply voltage = back e.m.f.—IR drop

it becomes evident that, in order to maintain the back e.m.f. and the supply voltage equal, and at the same time obtain electrical voltage balance according to the above equation, it is necessary to introduce a further supply voltage equal to the machine IR drop. This is effected by inserting a booster in the armature circuit of the pay-off reel drag generator.

In order to maintain the back e.m.f. of the pay-off reel drag generator proportional to line speed for all values of coil diameter, it can be seen from equation (2) that the excitation of this machine must be controlled to be proportional to coil diameter. Basically, a circuit is used which adjusts this excitation in such a manner as to balance the back e.m.f. against the voltage of a pilot exciter, driven at strip speed and having constant excitation adjusted to give an e.m.f. equal to the main generator voltage.

Tension Control

For constant tension, equation (1) indicates that the generated current must be held constant. As mentioned previously, in order to use the main generator voltage as a measure of the line speed and, at the same time, maintain the back e.m.f. of the pay-off reel drag generator equal to this line voltage, it was necessary to insert a booster in series with the machine armature to compensate for the IR drop. This booster can now be used as a means of controlling the current in the circuit, as it is the only voltage which can pass current around the circuit. The booster voltage is controlled by means of a system which compares the required armature tension-current with the actual armature current, and adjusts the booster voltage accordingly.

Speed Control of Side Trimmer

The side-trimmer motor must run at such a speed that the peripheral speed of the cutters is either equal to or slightly greater than the line speed.

Whilst the side trimmer is tied to the main generator as far as its supply voltage is concerned, this connection does not fully meet the requirements because, as indicated earlier, there is the inherent problem of IR drop in the motor armature, which causes the motor speed to be less than that fixed by the supply voltage. Once again it is the back e.m.f. which the motor is required to generate which governs its speed.

The required control can therefore be attained by injecting into the circuit, by means of a booster, a voltage equal to the IR drop in the motor armature. This then ensures that the back e.m.f. of the motor is always equal to the generator supply voltage, and the motor speed is always proportional to the line speed.

Prime Coiler Control

As an introduction to the method of control employed on the prime coiler, consider what would happen if the motor was connected across the main generator busbar and provided with no further control.

The coiler motor would endeavour to run at constant speed as fixed by the main generator voltage. However, as the coil diameter built up, the line speed would increase and the coiler motor would have to take more current to overcome the greater torque required due to the increasing coil diameter.

Furthermore, as the line speed, and hence the voltage of the pilot-exciter mentioned under the heading 'E.M.F. Control for Pay-off Reel', increased, it can be seen that the back e.m.f. of the machine would increase. Even under these conditions the current control circuit would still endeavour to maintain constant current, and in doing so would cause the booster voltage to reduce and finally reverse. In other words, the strip tension would be maintained even though the strip speed had increased. This increase in strip speed with the prime-coiler coil build-up would continue until either the coiler motor tripped out on overload or the booster of the pay-off reel drag generator tripped out first on over-excitation, depending on the relative values of the main generator voltage and the tension setting.

It is essential then to incorporate a circuit which will control the speed of the prime-coiler motor so that as the coil builds up, the motor is

slowed down in proportion, and the strip speed remains constant.

This can be achieved electrically by reducing the motor terminal voltage as the coil builds up. To effect this a booster is introduced into this circuit to inject a voltage in opposition to the main generator voltage. The basic circuit given in Fig. 3, with this and the previous additions, now becomes as in Fig. 4.

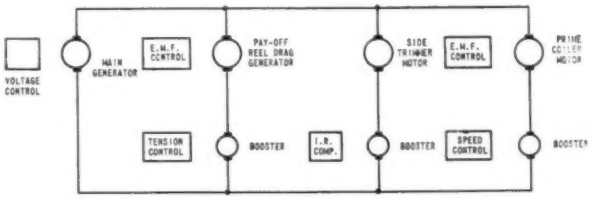


Fig. 4.—Boosters and controls for pay-off reel, side trimmer and prime coiler, added to basic circuit in Fig. 3.

As has been indicated, the main generator voltage is used as the electrical reference corresponding to the required line speed. Therefore a speed control circuit is used which adjusts the booster voltage in such a manner as to balance the pilot-exciter voltage against the main generator voltage and thus control the line speed in proportion to the main generator voltage.

Whilst this circuit would provide the necessary control if the prime-coiler motor field remained constant, it suffers from the following disadvantages.

1. If the coil-diameter build-up is say four to one, the prime-coiler motor must have a speed range of four to one. This would mean that the booster would have to develop a voltage equal to three-quarters the generator voltage when maximum coil diameter was reached. Also, since the tension is held constant by the pay-off reel drag generator, the torque required from the prime-coiler motor would cause it to increase its armature current as the torque requirements increased.

2. It will be realised that the horse-power required remains constant over the full speed range of the prime-coiler motor. Therefore, at one-quarter full voltage the current will be four times that at full voltage, and the motor would have to be designed for four times the required output at full voltage.

3. The booster would also have to be capable of supplying the maximum current at three-quarters of the generator voltage, and therefore would be of comparable size to the main generator.

In order to reduce the voltage of the booster and the size of the prime-coiler motor, this motor is designed to give the required horse-power at full field and full voltage. An e.m.f. control circuit is then incorporated, similar to that described for the pay-off reel drag generator. This circuit adjusts the e.m.f. of the motor by means of its field, and also enables the motor to develop the required torque without change of armature current. The booster now has only to correct for any error in this circuit, and provide the requisite IR drop voltage for any set value of tension.

Reject Coiler Control

The reject-coiler motor drives the reject coil at a strip speed of about one-twentieth of normal prime-coiling speed. Since this motor is never required to operate at any line speed above this, it would be uneconomical to feed it from the main generator, as it would have to be designed for its rated horse-power at one-twentieth of the main generator voltage, which would demand a motor having a commutator of comparable size to that of the prime-coiler motor. The reject-coiler motor is therefore fed from its own generator and so arranged that full voltage is applied at the reduced line speed, thus reducing the motor to an economical size for the required duty.

Since the reject coiler motor has its own generator it is not necessary to incorporate any booster in this circuit, because all compensation can be done on the generator itself. The basic circuit is therefore as shown in Fig. 5.

The main generator is still used as the main speed reference by switching the prime-coiler speed control circuit on to the reject-coiler generator.

With this motor it was found to be more economical, due to the relatively small machines involved, to accommodate for coil build-up by

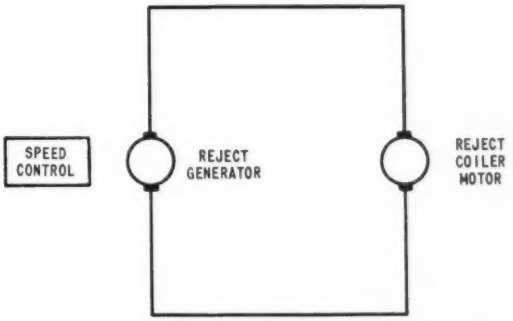


Fig. 5.—Basic circuit for reject coiler

means of the generator voltage control rather than incorporate a separate e.m.f. control as in the case of the prime coiler.

Summary of Main Control Features

Summarising the control features which have been described in this section, the main generator gives the main component of voltage for the individual machine control, and also acts as an electrical reference of the required line speed. It feeds the pay-off reel drag generator, side trimmer and prime coiler motors in parallel. For economic reasons the reject coiler motor is fed from its own generator, which is tied to the main circuit by means of a speed control circuit.

Coil build-up is compensated for on both the pay-off reel drag generator and the prime coiler motor by means of e.m.f. control circuits, whereas coil build-up on the reject coiler is compensated for by means of generator voltage control.

The pay-off reel drag generator is used to control tension by means of a current control circuit operating on the associated booster excitation, and the side-trimmer speed is held equal to or greater than line speed by means of an IR compensating circuit operating via its associated booster.

Actual line speed is maintained constant by means of a speed control circuit operating on the prime coiler motor via its booster, or on the reject coiler motor via its generator.

Operation of Line

With the electrical arrangement described, the line can be controlled by means of four pushbuttons labelled ' run ' ' hold ' ' stop ' ' thread '.

Reject or prime coiling can be selected by means of a selector switch on the main control desk.

If prime coiling is selected, operation of the ' run ' pushbutton causes the line to run up to its top speed. Pressing the ' hold ' pushbutton at any intermediate speed between thread and top speed causes the line to continue to run at the chosen speed. The ' stop ' button causes the line to run down to standstill under controlled deceleration. Operation of the ' thread ' pushbutton causes the line to run up or down to a thread speed of approximately one-twentieth full line speed from either below or above this speed.

If reject coiling is selected, the operation of the line is as for prime coiling with the exception that pressing the ' run ' pushbutton then causes the line to run up to a top speed of approximately one-twentieth full line speed.

DETAILED STUDY OF CONTROL CIRCUITRY

Line Speed Control

As previously stated, the main generator is used to control the line speed. For this purpose the generator field is controlled by a motorised rheostat, the drive motor of which is fed from an acceleration exciter as shown in Fig. 6. This pilot motor is controlled by means of the pushbuttons already described.

Due to the high operating speed it is imperative that the line must not fail to stop when the ' stop ' button is depressed. To safeguard against possible failure of the ' stop ' circuit, the following back-up protection is included. The generator field is arranged in two halves in the form of a bridge circuit by means of resistors R1 and R2 having the same resistance values as the two halves of the field. Across the balance points of this circuit is placed the auxiliary coil of a timing relay, the main coil of which is fed in parallel with the main stopping relay. Operating the line ' stop ' push-button de-energises the main stopping relay and also the main coil of the timing relay, which has a delayed drop-out time of ¾ second. Under normal operating conditions, de-energising the

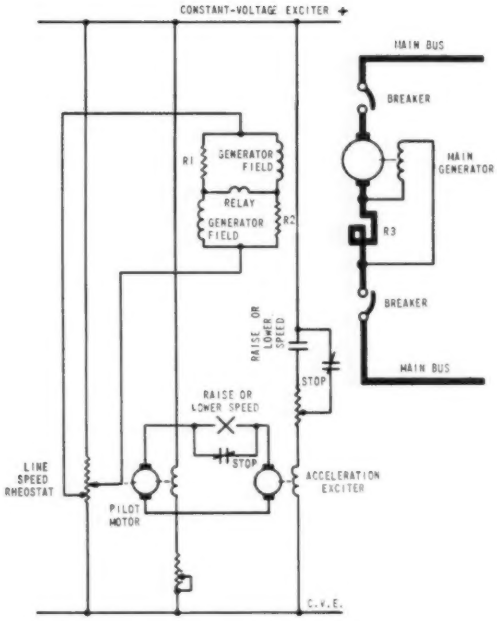


Fig. 6.—Circuit for line speed control by main generator

main stopping relay causes the pilot-motor-operated rheostat in the main generator field to run down to zero. As the current begins to fall in the two halves of the generator field their inductive effect causes an out-of-balance current to flow in the auxiliary coil of the timing relay, thus re-energising it. If however the pilot motor fails to start, the timing relay is not re-energised, and, after the requisite time delay, drops out and brings the line to a standstill under dynamic braking.

Due to the various tension loadings required on the line the actual generator current varies appreciably, and the IR drop in the generator would normally cause its output voltage to vary. In order to obtain close regulation of this voltage, and therefore the line-speed electrical reference, the generator is equipped with an auxiliary field fed from a resistance (R3) in its armature circuit, which boosts its field excitation in proportion to the actual load current and therefore maintains its output voltage reasonably constant.

E.M.F. Control of Pay-off Reel Drag Generator

In the previous section under this heading it was shown that it is necessary to maintain the back e.m.f. of the pay-off reel drag generator constant for all values of coil diameter. It is not possible to measure this back e.m.f. directly, since the voltage across the armature of the machine is the sum of the back e.m.f. and armature IR drop. A circuit must therefore be devised which enables these two components to be separated, and a bridge circuit is used as shown diagrammatically in Fig. 7. One arm of the bridge is made up of the pay-off reel generator armature and compole resistance, and the other arm comprises the armature of a pilot exciter and fixed resistances. The pilot exciter is driven from idle rolls on the line and excited from the constant-voltage exciter, its output voltage therefore being proportional to line speed.

An analysis of this circuit, using Kirchhoff's laws (see Appendix), indicates that the current in the balance arm is proportional to the difference in the e.m.f. of the pay-off reel generator and the pilot exciter.

Utilisation of this fact results in the control circuit shown in Fig. 8. In the balance arm of the bridge circuit is inserted the control winding of a

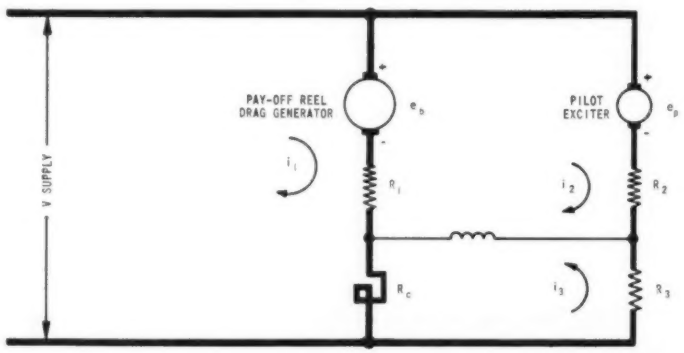


Fig. 7.—Bridge circuit used in e.m.f. control of pay-off reel drag generator

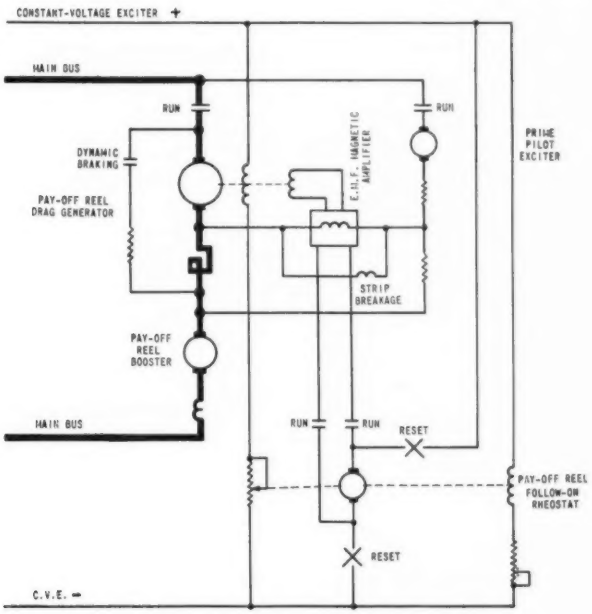


Fig. 8.—Control circuit for pay-off reel drag generator

magnetic amplifier. This amplifier feeds the auxiliary field of the pay-off reel drag generator and also the pilot motor of a follow-on rheostat controlling the main field. As the coil diameter on the pay-off reel falls, the drag generator accelerates and its e.m.f. tends to increase, causing the output of the magnetic amplifier to increase and thus decrease the auxiliary field of the drag generator. When the output of the magnetic amplifier reaches a certain value it operates the motorised rheostat, which moves to give a permanent adjustment to the machine field. This procedure continues over the complete range of coil-diameter change.

The circuit is also provided with a protective device for strip breakage, which takes the form of a relay connected across the magnetic-amplifier control winding. If the strip breaks, the pilot-exciter voltage falls to zero and a large voltage appears across the control windings, thus operating the relay and causing an emergency shutdown of the line.

Tension Control of Pay-off Reel Drag Generator

The circuit used for maintaining the armature tension-current of the pay-off reel generator at the desired value is shown in Fig. 9. In this circuit the pay-off reel booster receives its excitation from the control/reference exciter loop. The reference exciter is a constant-speed machine incorporated in the exciter set, and obtains its main excitation from the constant-voltage bus via a tension-setting rheostat on the main control desk ; its voltage is therefore proportional to the desired tension in the strip. The current exciter receives its excitation from a heavy-current field in the main armature circuit of the pay-off reel drag generator, and its excitation is therefore proportional to the actual current in this circuit. The voltages of these two exciters are backed off against one another, and the resultant voltage is used as the excitation voltage of the booster. Any variation between the actual armature current and the desired current causes the booster to generate a voltage of such a polarity and magnitude as to correct the error.

This booster is also utilised to provide stall tension, in order to maintain a tight coil when the line is at standstill, and also forward and reverse inching of the pay-off reel.

The foregoing scheme covers the requirements for steady running conditions, but during acceleration and deceleration further compensation is necessary if the strip tension is to be maintained at the required value.

When the line is being accelerated, an accelerating torque must be applied to the rotating parts of the pay-off reel system, and if the electrical load is not reduced by an amount equal to the additional inertia load, the tension in the strip will increase during acceleration. Conversely, the tension will decrease during deceleration.

In order to avoid this variation, control windings are added to the reference exciter to provide suitable adjustment of the generator armature current under accelerating and decelerating conditions.

The method of feeding these fields in order to enable them to supply the correct compensation under all operating conditions can be ascertained from the following mathematical analysis.

The moment of inertia J of the pay-off reel system can be separated into two parts ; the moment of inertia of the rotating armature, gears and mandrel, which is constant, and the moment of inertia of the coil, which is dependent on strip width and coil diameter.

As a reasonable approximation, assuming a solid mandrel

$$J = K_1 + K_2 WD^4 \quad \ldots\ldots (4)$$

where W is the width of the strip

D is the diameter of the coil.

The torque Ta required to accelerate this inertia is proportional to the angular acceleration required.

$Ta \propto J \times$ angular acceleration $\ldots\ldots$ (5)

Now the angular acceleration is proportional to linear acceleration of strip/D.

$\therefore Ta \propto J \times 1/D \times$ acceleration of strip $\ldots\ldots$ (6)

The torque of an electrical machine is proportional to the armature current $\times$ the field flux.

$Ta \propto Ia \times \phi \quad \ldots\ldots$ (7)

From (6) and (7)

$Ia \propto J \times 1/D \times 1/\phi \times$ acceleration of strip (8)

From the previous section under ' Line Speed Control ' it will be remembered that $D \propto \phi$.

$\therefore$ (8) becomes

$Ia \propto J \times 1/D^2 \times$ acceleration of strip $\ldots\ldots$ (9)

Substituting for J from (4)

$Ia \propto (K_1 + K_2 WD^4) \times 1/D^2 \times$ acceleration of strip $\ldots\ldots$ (10)

$\therefore Ia \propto (K_1/D^2 + K_2 WD^2) \times$ acceleration of strip $\ldots\ldots$ (11)

The above analysis shows that two inertia compensating fields must be provided, and that the currents in each of these fields must be arranged to vary in proportion to the acceleration of the strip. Coupled with this variation, one field current must vary in inverse proportion to the square of the coil diameter, and the other in proportion to the strip-width times the square of the coil diameter. These facts lead to the following type of control.

The acceleration of the line is dependent upon the speed of the pilot motor driving the main generator field rheostat, and consequently on the voltage of the acceleration exciter which supplies this motor. The use of this voltage to feed the inertia compensation circuits automatically provides the correct value for the strip acceleration.

The first inertia compensation is effected by connecting one of the compensating fields across the acceleration exciter voltage in series with a resistance graded to give a current in inverse proportion to the coil diameter squared.

The remaining compensation is effected as follows.

The second compensating field is fed from the acceleration exciter voltage via a potentiometer so graded that the applied voltage is proportional to the coil diameter squared. In series with the field is then connected a rheostat calibrated to strip width and mounted so that the operator

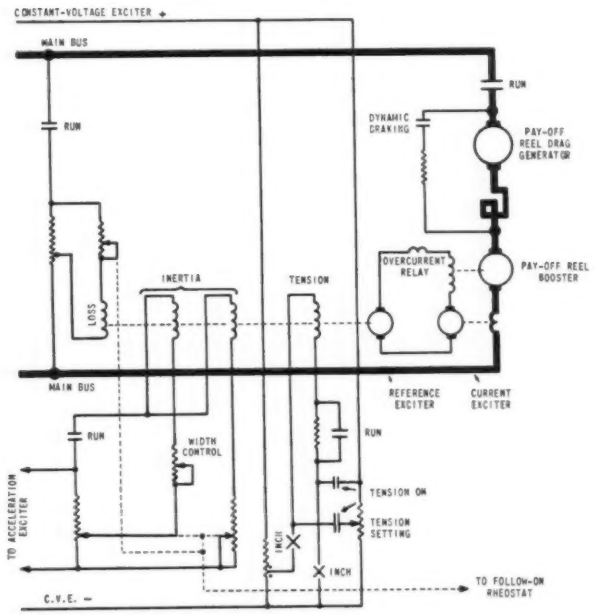


Fig. 9—Circuit for maintaining armature tension-current in pay-off reel drag generator

is able to set it to correspond with the actual strip width.

It must now be ensured that the position of these variable resistances always corresponds to the actual coil diameter. From the description of the e.m.f. control on the pay-off reel drag generator it will be realised that the position of the follow-on rheostat is a direct measure of the coil diameter, and the resistance tracks are therefore coupled to this rheostat.

One further compensation remains, and this is for the variable no-load losses of the pay-off reel drag generator itself. There are several no-load losses which vary with some power of the speed. When the total of these is plotted against the motor speed, a more or less parabolic curve is followed, i.e. the total losses are approximately proportional to the square of the speed. This means :—

$$\text{Loss power} \propto N^2 \propto T_L \times N \quad \ldots\ldots\ldots\ldots (12)$$

$$\therefore T_L \propto N \propto S/D \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

where T_L = loss torque

N = machine speed in r.p.m.

S = strip speed

D = coil diameter

From relationship (7)

$$\text{loss current} \propto T_L/\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

From the previous section under ' Line Speed Control ' $\phi \propto D$

$$\therefore \text{loss current} \propto T_L/D \propto S/D^2 \quad \ldots\ldots\ldots\ldots (15)$$

As described in the previous section under ' Line Speed Control ', the main-generator voltage is directly proportional to the line speed, so this voltage can be used as the supply source for the compensatory field on the current-reference exciter. The field is fed from the main-generator bus via a series resistance, graded to modulate the current in inverse proportion to the coil diameter squared. For the same reasons as previously given, this resistance forms a further track on the follow-on rheostat.

Speed Control of Side Trimmer

The side-trimmer control circuit is as shown in Fig. 10. As explained in the previous section under the above heading, a booster is used to compensate for the IR drop in the motor armature circuit.

The torque required for trimming a given thickness of strip is more or less constant at all speeds. Consequently, since the motor has a constant field excitation, apart from a small adjustment range, its armature current is constant at all speeds. The IR drop in the armature

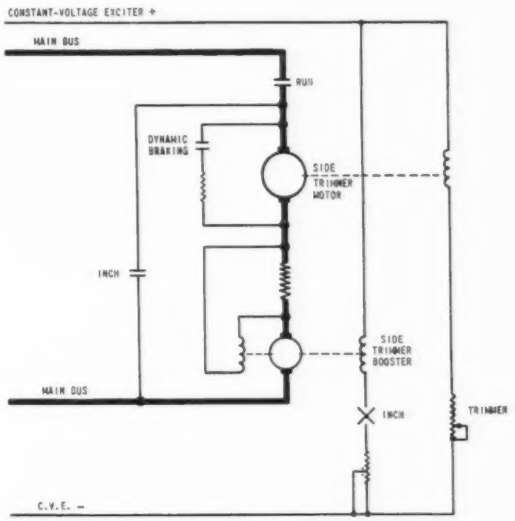


Fig. 10.—*Control circuit for side trimmer*

circuit is therefore the same value for all steady-state running conditions, and the output voltage from the booster required to compensate for this is also constant. However, under accelerating and decelerating conditions the armature current no longer remains at the steady running value, and consequently a different booster voltage is required. In order to ensure that the booster voltage is at all times proportional to the armature current, the booster is excited from a series resistance in the trimmer-motor armature circuit. By this means correct IR compensation is effected under all running conditions.

The booster is also used for inching, by switching in an auxiliary field fed from the constant-voltage bus via reversing contactors.

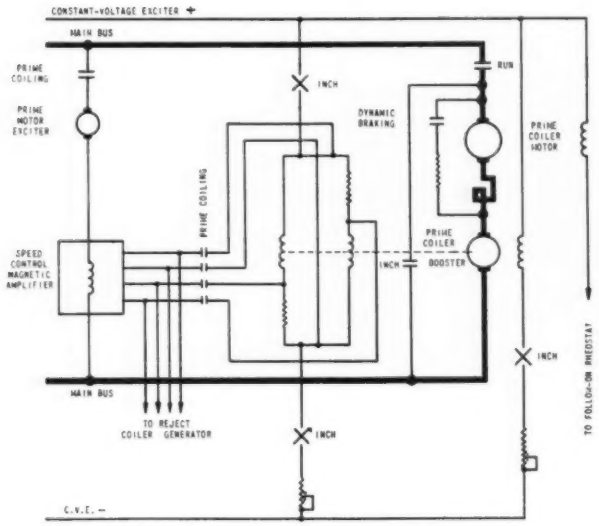


Fig. 11.—Speed control circuit for prime coiler

Prime Coiler Control

The speed control circuit for the prime coiler is shown in Fig. 11.

The speed-control magnetic amplifier provides the excitation for the booster in series with the armature of the coiler motor. As the prime coil builds up, the pilot exciter is driven slightly faster and therefore its voltage increases. The control is arranged so that this voltage change causes the magnetic amplifier to alter the booster voltage in such a manner as to reduce the terminal voltage of the prime-coiler motor, thus reducing its speed.

It is necessary to use a push-pull magnetic amplifier because with certain low tension settings the booster voltage may have to reverse under decelerating conditions.

As discussed in the previous section under ' Prime Coiler Control ', an e.m.f. control is also incorporated on the prime coiler. This circuit is similar to that described in this section for the pay-off reel drag generator, and therefore requires no further comment. The booster is also used for inching, by switching the booster fields on to the constant-voltage bus via reversing contactors.

Reject Coiler Control

As discussed under this heading in the previous section, the reject coiler motor is fed from its own separate generator, and the circuit is as shown in Fig. 12.

When the reject coiler is selected by the operator, the speed-control magnetic amplifier is switched over to the reject-coiler generator field.

It will be noted that the main generator supply voltage is still used as the line speed reference. Line speed is therefore still controlled in a similar manner to that described earlier, the only exception being that, as previously mentioned, operation of the ' run ' pushbutton will cause the line to run up to a top speed of one-twentieth full line speed.

As the main generator voltage is increased, the speed-control magnetic amplifier will increase the reject-coiler generator voltage to allow the reject-coiler motor to maintain the necessary line speed.

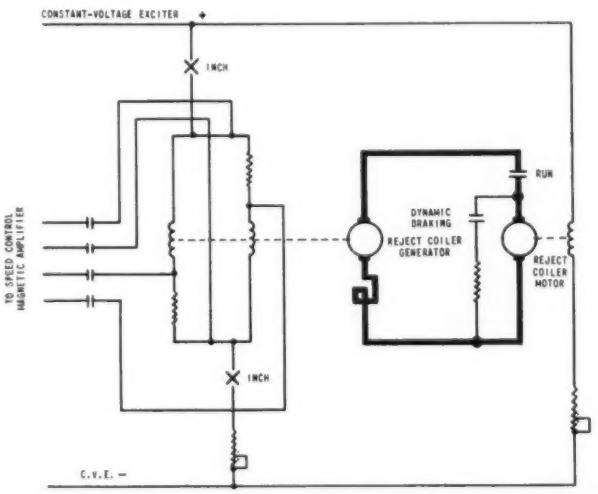


Fig. 12.—Control circuit for reject coiler

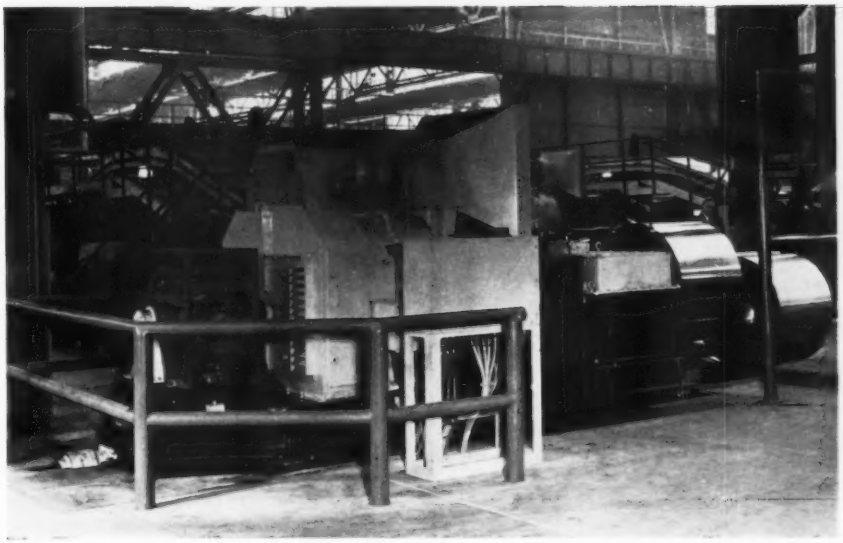


Fig. 13.—Forced-ventilated pay-off reel drag generator

Forward and reverse inching of the reject coiler is facilitated by feeding the generator field from the constant-voltage exciter via reversing contactors.

THE ELECTRICAL EQUIPMENT AT VELINDRE

Drag Generator and Prime Coiler Motor

The pay-off reel drag generator and prime coiler motor, in spite of the slight difference in rating, were designed as duplicate machines. They are of the C.S. class having two pedestal-mounted ring-lubricated sleeve bearings. Forced ventilation was chosen in order to give adequate cooling over the wide operating-speed range. As the drag generator has to move on a sliding bed for strip alignment, the machine and its ventilation equipment is a self-contained unit. Fig. 13 shows the compact arrangement of the machine with its ventilation fan and dry-type filter unit mounted on top. The cooling air is directed in at the top of the machine and discharged over the commutator. The commutator end is enclosed, but access doors with louvred air outlets are provided.

The drive ends of these machines are coupled respectively to the pay-off reel and prime coiler mandrels through reduction gear-boxes, and the non-drive ends are fitted with 24 inch diameter electromagnetic brakes and overspeed tripping devices.

Side Trimmer and Reject Coiler Motors

The smaller speed ranges of the side trimmer and reject coiler motors make forced ventilation unnecessary, and these machines are of the totally enclosed closed-air-circuit type. They are of the CAM class with bearings of the endshield ball and/or roller type. With this type of motor, shown on the left of Fig. 14, two fans are mounted on the motor shaft, one to circulate air between the motor and the air heat exchanger on the top of the motor, and the other to blow outside air through the tubes of the heat exchanger. Electromagnetic brakes of 14 and 10 inch diameter respectively are provided on the two motors, and also overspeed devices. A tacho-generator for speed indication is also provided on the side-trimmer motor.

Motor-generator and Exciter Sets

Installed in the basement below the two lines are the motor-generator sets, exciter sets and control panels.

The motor-generator set for each line is housed in a separate room running parallel to the line, one

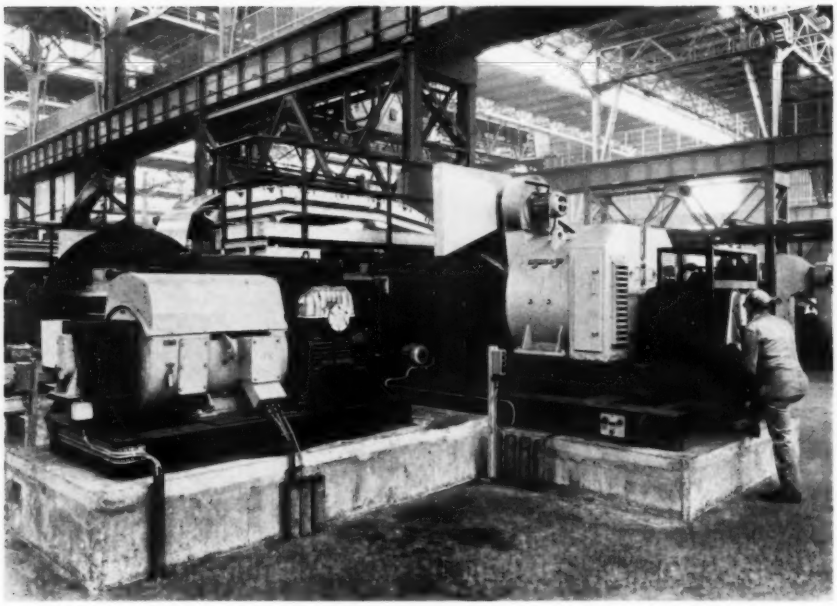


Fig. 14.—*Closed-air-circuit reject-coiler motor* (*left*) *and forced-cooled prime-coiler motor* (*right*)

of these sets being shown in Fig. 15. A 300 h.p. squirrel-cage motor running at 985 r.p.m. drives the main generator, the reject-coiler generator, and boosters for the pay-off reel, edge trimmer and prime coiler. All the machines are of the screen-protected type, the main generator being of the C.S. class and the remaining d.c. machines of the CAM class. The main generator is designed for a continuous rating of 120 kW but is capable of a peak rating of 600 kW to cater for the acceleration of all drives on the line together with the coils on the pay-off reel and prime coiler. Correspondingly, the driving motor is capable of a peak of 900 h.p. and is designed for direct-on-line starting from the 3.3 kV works supply.

Fig. 16 shows one of the exciter sets, comprising the exciters for current, reference, constant voltage and acceleration, all of the CAM protected class. The set is driven by a 50 h.p. squirrel-cage induction motor of the LK protected type, running at 1500 r.p.m. and fed from the 415 V, 3 phase, 50 cycle, shop supply.

The main motor-generator set is started from a control pedestal situated in the generator room

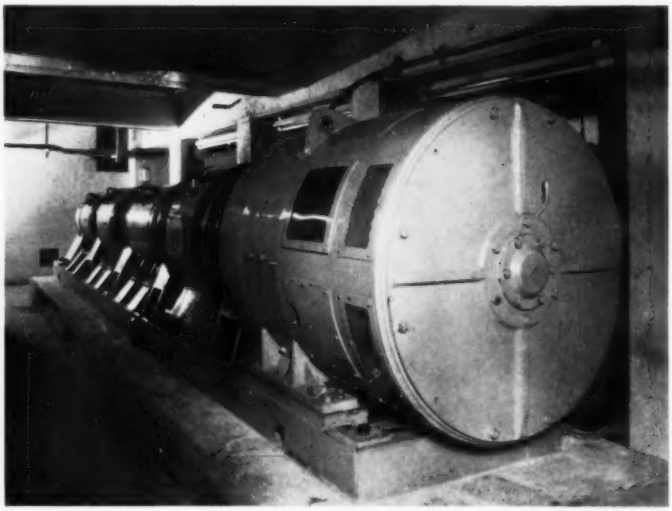


Fig. 15.—*Motor-generator set*

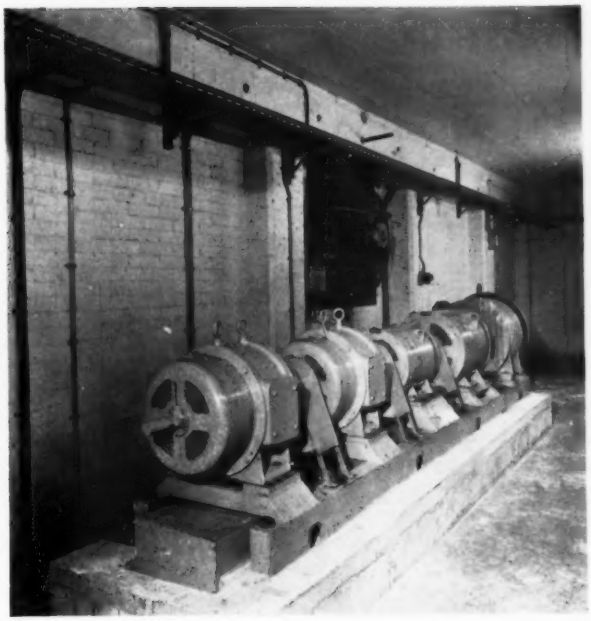


Fig. 16.—*Exciter set*

and remotely controlling a circuit-breaker housed in one of the substations. Starting of the exciter set is effected at the appropriate control board.

Control Room

The control room is situated at right angles to the generator rooms and interconnected with them. In it are housed the contactor boards for the two lines, a general view of one of these being shown in Fig. 17. Behind each board perforated metal cases, mounted on channels above floor level, contain the resistances required for pre-setting particular control circuits and for dynamic braking of the line motors.

In the foreground of Fig. 17 can be seen two cubicles housing magnetic amplifiers and resistance units. Each magnetic amplifier is mounted on a withdrawable chassis so that it can easily be replaced by a spare unit should a fault occur.

Fig. 17.—*Contactor board (right), with magnetic-amplifier cubicles in foreground*

In this room are also mounted the motorised rheostats for common and individual control of the line machines. These rheostats, one of which is shown in Fig. 18, are of the roller type having a contact-making roller running over a vertical stack

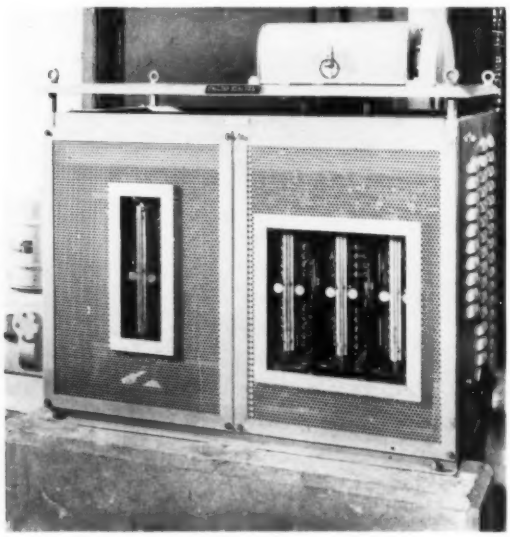


Fig. 18.—Roller-type motorised rheostats

of contacts. They are of a type developed primarily for the frequent operation associated with rolling mill duty, and enable, where necessary, a large number of tracks to be coupled together and operated by a single drive. The three rheostats for each line cover the line speed control and field control of the pay-off reel and prime coiler machines.

Acknowledgement

The author expresses his appreciation of the permission given by The Steel Company of Wales Limited to publish this article and reproduce the photographs and diagrams of that Company's plant.

APPENDIX

Analysis of the circuit shown in Fig. 7, using Kirchhoff's laws.

$$V - e_b = (i_1 - i_2)\,R_1 + (i_1 + i_3)\,R_c \quad \ldots\ldots (16)$$

$$V - e_p = i_2\,R_2 - i_3\,R_3 \quad \ldots\ldots (17)$$

$$O = (i_1 + i_3)\,R_c + i_3\,R_3 \quad \ldots\ldots (18)$$

From equation (18)

$$-\,i_1 = i_3\,\frac{(R_c + R_3)}{R_c} \quad \ldots\ldots (19)$$

Subtracting (16) from (17)

$$e_b - e_p = i_2\,(R_1 + R_2) - i_3\,(R_c + R_3) - i_1\,(R_1 + R_c) \quad \ldots\ldots (20)$$

Substituting equation (19) in equation (20)

$$e_b - e_p = i_2\,(R_1 + R_2) - i_3\,(R_c + R_3) + i_3\,\left(1 + \frac{R_3}{R_c}\right)\,(R_1 + R_c) \quad \ldots\ldots (21)$$

Re-arranging equation (21) gives

$$e_b - e_p = i_2\,(R_1 + R_2) + i_3\,\left(R_1 + \frac{R_1\,R_3}{R_c}\right) \quad \ldots (22)$$

$$\text{If } \frac{R_1}{R_2} = \frac{R_c}{R_3} \quad \ldots\ldots (23)$$

equation (22) becomes

$$i_2 + i_3 = \frac{e_b - e_p}{R_1 + R_2} \quad \ldots\ldots (24)$$

Since R_2 is arranged to be much greater than R_1, equation 24 becomes

$$i_2 + i_3 \simeq \frac{e_b - e_p}{R_2} \quad \ldots\ldots (25)$$

Equation 25 indicates that the current in the balance arm is proportional to the difference in the e.m.f. of the pay-off generator and the pilot exciter, as discussed on page 38.

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